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THESIS

A LOW-COST MAN-PORTABLE FREE-SPACE OPTICS COMMUNICATION DEVICE FOR ETHERNET APPLICATIONS

by

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December 2004

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13. ABSTRACT (maximum 200 words)

This thesis sought to design and implement a low-cost, portable, Free-Space Optics (FSO) communications device for Ethernet applications. Under some circumstances such a device would have utility at a Combat Operations Center (COC), a Field Artillery Position, or wherever else fiber optic cable is used in garrison or field. The design was based on commercial off the shelf components originally designed for fiber optic applications. Based on a 155 megabits per second (Mbps) media converter, the design used two fiber optic transceivers, coupled to collimating lenses to pass data over free-space. Sustained data rate of 100 Mbps was achieved with full network functionality on the optical bench with a low-power (0.5mW) laser diode transmitter without focusing optics on the receiver. The laser diode power(mounted on device), was measured with acceptable losses up to 300 ft during testing using a photodiode with focusing optics. The findings indicate that the system with proper collecting optics could be optimized for free-space communication at short to moderate ranges.

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A LOW-COST MAN-PORTABLE FREE-SPACE OPTICS COMMUNICATION DEVICE FOR ETHERNET APPLICATIONS

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ABSTRACT

This thesis sought to design and implement a low-cost, portable, Free-Space Optics (FSO) communications device for Ethernet applications. Under some circumstances such a device would have utility at a Combat Operations Center (COC), a Field Artillery Position, or wherever else fiber optic cable is used in garrison or field. The design was based on commercial off the shelf components originally designed for fiber optic applications. Based on a 100-megabits per second (Mbps) media converter, the design used two fiber optic transceivers, coupled to collimating lenses to pass data over free-space. Sustained data rate of 100 Mbps was achieved with full network functionality on an optical bench with a low-power (0.5 mW) laser diode transmitter without focusing optics on the receiver. The laser diode power (mounted on the transceiver), was measured with acceptable losses up to 300 ft during testing using a photodiode with focusing optics. The findings indicate that the system with proper collecting optics could be optimized for free-space communication at short to moderate ranges.

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EXECUTIVE SUMMARY

Free-Space Optics (FSO) in data communication applications is mature technology, in successful use all over the world. There are many limitations to FSO implementation, mainly due environmental and physical constraints. Free-Space Optics links require line of sight and are highly susceptible to degradation due to fog, rain, etc. However, given favorable conditions and Line-of-Sight (LOS), FSO is an efficient and inexpensive alternative to fiber optic cables. This fact is exploited by a number of companies who have emerged as market leaders in this growing niche of the communications industry. The devices that are presently available commercially are bulky and expensive. This thesis explored the design and implementation of a man-portable FSO device for military field use, at applications such as at Marine Corps Combat Operations Centers (COC), Field Artillery positions and at antenna farms as an alternative fast link between communications nodes that would normally need fiber optic cable. If successfully optimized, such a device could prove to be time and money saving alternative in some military communications applications.

Using commercially available parts, a portable FSO device was built, based on a 100-Mbps media converter chip. This device successfully established an FSO link over free-space under laboratory conditions (on an optical table at a range of 5 ft.) using low power and no collection optics. Normal functionality was observed on all network applications. A data rate of 100 Mbps was sustained during all operations. Tests confirmed that the transmitted beam was detectable at a range up to 300 ft, with and without receiver optics. It is believed that the device could be optimized with a higher powered transmitter, a larger detector along with the incorporation of collimating and focusing optics.

Further research in optics and transmitter/receiver components is necessary to fully realize the benefits of this portable device that has application both in garrison as well as in field.

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I. INTRODUCTION

The goal of this thesis was to design, implement and test a low-cost, man-portable, Free-Space Optics (FSO) communication device that may be used to link Ethernet based networks or devices in lieu of fiber optic cables in military field applications. In particular, the design was aimed to be applicable for use at a Marine Corps Combat Operations Center (COC), or a Field Artillery position. This introductory chapter describes the motivation for this work, and covers the organization of follow-on chapters.

A. BACKGROUND

There are many means of linking Ethernet networks or subnets. Wireless networking (WiFi) or the 802.11 standard has been in the forefront of interest in recent times, while we continue to use established technology such as fiber optic cable and various Unshielded Twisted Pair (UTP) standards. Each method has advantages and drawbacks, and clearly no one medium is ideal for all applications. Free-space Optics (FSO) is one such means of linking Ethernet nodes. It is a technology that has gained a niche during recent years as a so called *last mile solution*. The term “last mile” describes the often troublesome means of connecting a Local Area Network (LAN) to a Metropolitan Area Net Work (MAN) or connecting a physically separated subnet (or even a single host) to a parent LAN efficiently. (See, for example, Refs. [1, 2].) Fiber optic cable is certainly an option, yet is significantly costly to implement for LAN applications, especially in metropolitan areas. Initial cost of fiber infrastructure could be prohibitively high for small or medium sized businesses when connectivity could involve digging or modifying existing structures or roads, requiring secondary construction and permits, which in turn usually entail additional delays and cost. (See, for example, Refs. [1, 2, 3].) Given certain constraints, FSO technology is a simple, relatively low-cost alternative to fiber. In many short distance applications it is a practical solution, considerably less costly than fiber and capable handling high enough data rates to satisfy most applications. In the author’s opinion, speed and ease of deployability favors FSO over other media as well. During disaster recovery operations such as the aftermath of a natural disaster, FSO technology can be rapidly deployed to restore vital computer links. However, there are

many limitations to the use FSO technology. Free-Space Optics require line of sight and is subject to atmospheric attenuation. Fog, rain, and other atmospheric conditions affect FSO links and limit the link lengths as will be shown elsewhere in this thesis. Safety concerns limit the amount of power that may be deployed in a system. Even with these limitations, FSO is a viable alternative to fiber cable in some applications. A recent NPS thesis compared the suitability of various wireless technologies for Marine Corps field command and control entities. After field testing FSO, Microwave, 802.16 and others, the study concluded that, for line of sight (LOS) conditions, FSO is the best suited technology for Marine Corps needs [4].

Free-Space Optics technology currently exists commercially and is a growing niche market. There are several companies that exclusively produce FSO linking devices, and offer off-the-shelf as well as custom designed devices to link physically separated Ethernet nodes. Lightpointe Incorporated of San Diego is one such company [4]. Another prominent name in the FSO business is AirFiber Incorporated, also based in San Diego, California. (See, for example, Refs. [1, 2, 3].) Lightpointe's product line offers a 52-Mbps device that has a range of 5000 meters. The company website claims the deployment of over 2000 FSO devices in 60 countries [5]. Some established names in electronic communications have also recently entered the fray. Canon Corporation is an example of the latter. Canon's high end FSO device is advertised as capable of sustained data rates of 1.25 Gbps up to a distance of 1 km. Other models with lower data rates are capable of links up to 2 km [6].

These companies sell off-the-self devices or would custom design a system to suit a user's needs. Typically an FSO device is mounted on a rooftop or side of a building. Some have advanced self alignment systems built in. (See, for example, Refs. [4, 5, 6].) Telephone and email inquiries to various companies suggested that the typical cost of a 1.25 Gbps link between two buildings separated by 500 meters is about $10,000.

This thesis designed and implemented a prototype man-portable FSO system that may take the place of a fiber cable to link two nodes of an Ethernet network. The military-grade fiber optic cable in wide use, CX-11230, is costly and bulky. An 8 ft length of the cable is currently priced at about $1200 [7]. In many field applications such as at a

battalion size combat operations center or at a field artillery position, high-speed broadband data communication is desirable but not always possible due to the constraints of time, cost and the logistics (of carrying a bulky reel of fiber to the field.) The author, based on his experience as a field communications officer, believes that a low-cost, portable, FSO device has a utility value in a Marine Corps COC or an antenna farm. Used in lieu of fiber cable for fast, limited distance use under some circumstances, such a device could enhance communications efficiency.

B. APPROACH

Having delved in to the subject during the course of a year, the author believes that a system as described above is not commercially available. This thesis will show that a viable device could be designed and implemented for less than $1000, and that mass-produced devices would cost significantly less. We will show that a man-portable self-contained device could be designed and constructed using Commercial-Off-The-Shelf (COTS) components and that such a device could be optimized for longer distances and higher power by careful selection of wavelength, laser power and receiving and transmitting optics.

C. THESIS ORGANIZATION

Chapter II covers the theory behind FSO. We discuss the underlying physics that enable us to predict link distances, select the right components and make educated choices in such design parameters as power and wavelength. In this chapter we also discuss the safety issues that have to be addressed when dealing with any laser device, and the international and US regulations that applies to FSO.

Chapter III details the subsystems and their individual designs. Each subsystem is covered in detail and the design decisions discussed. We explain the choice of components, their individual merits and the reasons for choosing a particular component.

Chapter IV is a discussion of the results and contains the author's conclusions. Recommendations for further research are covered in this chapter as well.

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II. THEORY

This chapter introduces the current status of Free-Space Optics technology. The origin of FSO technology and its basic operation will be presented. Additionally, the basics behind the types of signals used in Ethernet transmission and the various conversions we will apply to signals to make them suitable of free-space transmission is covered. A brief discussion on laser transmitter operating principles and link margin analysis as it applies to an FSO system is also included. This chapter introduces the expected sources of loss when a laser beam is transmitted through the atmosphere and the important parameters of laser diodes and optical receivers.

A. AN INTRODUCTION TO FREE-SPACE OPTICS

1. History and Evolution of FSO

The concept that a light beam could be used as a medium to transmit information is hardly new. None other than Alexander Graham Bell is credited with the idea; Bell and Charles Tainter patented a device they called the *Photophone* in 1880 (Fig. 1.) By using a series of mirrors and lenses, they were able to modulate a voice signal on to a ray of sunlight and send it to a receiver 200 meters away [8]. In the *Photophone,* voice sound waves were directed on to a mirror that was used to reflect a beam of sunlight on to a similar mirror on a receiver. Voice sound waves caused this mirror to vibrate, thereby varying the intensity of the received ray. The receiver then converted these variations back to sound waves reproducing the voice [8]. The modulation scheme used by Bell is known as Intensity Modulation or IM. This method lends itself well to today's digital communications where the variations we have to worry about are just two: one and zero, or high and low. (See, for example Ref. [9].)

Engineers have known since this period that light could be used in this fashion to communicate. Indeed, in the period immediately following the demonstration of the first laser in 1960, there were several papers published that called for the exploitation of the new technology for space communications [10]. The cost and bulk of early lasers prevented rapid development of FSO technology. Another reason could be the lack of an obvious use outside of military and space applications. We simply did not have widespread

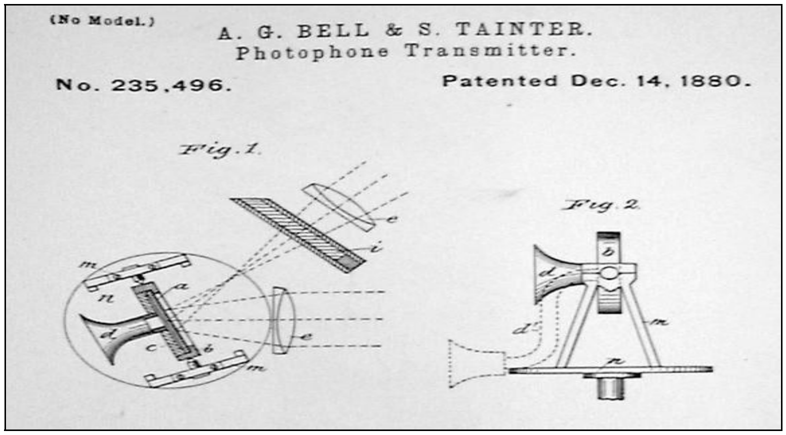

Figure 1. Patent for the Photophone filed by Alexander Graham Bell and Charles S. Tainter. (From Ref. [8].)

computer networks outside of universities, large corporations and the government. With the exponential growth of the internet and extensive use of information systems in the late 1980s to present, demand for bandwidth and speed has driven research into methods of fast inexpensive modes of data communications. As a result, FSO technology has been rediscovered in recent years as a potential solution for the last mile bottleneck discussed in the previous chapter. Additionally, advances in laser diode and photodetector technologies have made those devices relatively inexpensive and ubiquitous, allowing FSO to compete as a viable alternative to fiber both in speed as well as in cost. The next several sections of this chapter, will present the major subsystems of a generalized FSO system.

B. COMPONENTS OF AN FSO SYSTEM

1. Major Subsystems

Our discussion of theory behind an FSO device is best accomplished by individual treatment of major subsystems. Essentially, the system can be thought of as an interface between four components. These are:

a) Copper media input/output

b) Media converter

c) Laser transmitter

d) Receiver

Figure 2 is a block diagram of the system. We will discuss the functional theory of each of these subsystems below.

a. Copper Media Input/Output (I/O)

Unshielded Twisted Pair (UTP) is the most commonly used media today for Ethernet transmissions. The IEEE protocol 802.3, commonly referred to as Ethernet, enables either 100 megabits per second (Mbps) or 10 Mbps transmissions of data on two or four-wire twisted pair. The 100-Mbps standard is referred to as 100BASE-TX (two wire) or 100BASE-T4 (four wire.) The FSO device is designed to accept a standard RJ-45 male jack to connect the UTP cable. The incoming signal is sent through a 1:1 transformer in order to isolate it from the parent network. The I/O system also contains filters to manage the input noise level. On the output section, the signal is sent through another 1:1 transformer. It should be noted that the signals received at the I/O subsystem are

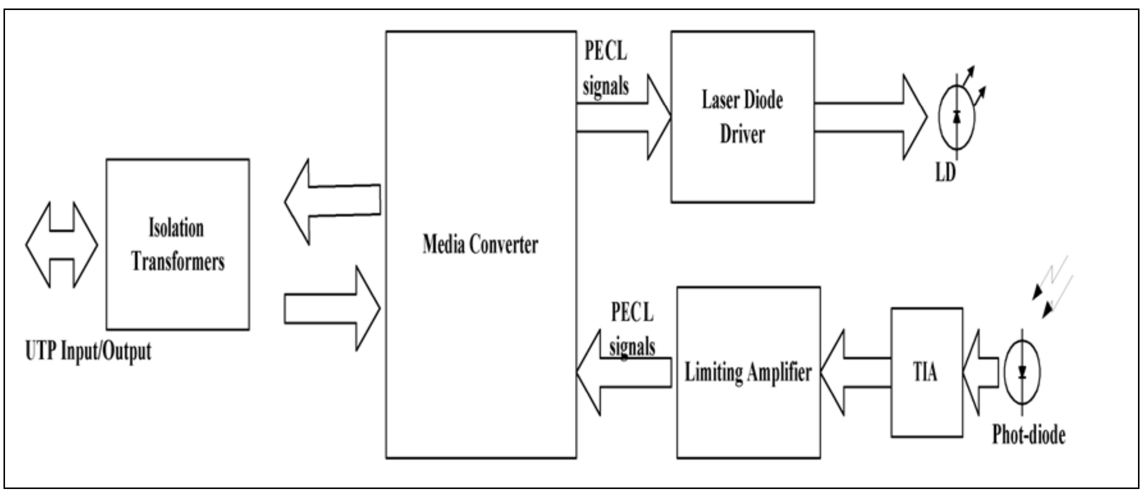

Figure 2. Block diagram of the FSO system.

not streams of simple binary digits. Rather, Ethernet packets containing digital data transmitted over copper or fiber in Ethernet networks are usually encoded using a scheme known as Manchester Encoding or variations of it. (See for example, Ref. [11].) The reason for this conversion is avoid errors as well as to eliminate the need for a separate clock signal. (See for example, Ref. [11].) When data is transmitted as simple binary digits, i.e., “1”s and “0”s at high-speeds over a network, long sequences of homogenous digits

could become indistinguishable from one another to a receiving device, thus causing errors at the receiver. Figure 3 shows a Manchester encoded bit stream along with its representative data. In this scheme there is always a transition at the middle of a bit interval. A “1” is represented by a downward transition and a “0” is indicated by an upward transition. Since the transition only takes place at the center of the bit interval, a separate clock signal is not needed. The receiving device can clock the incoming bits based on their transitions. (See for example, Ref. [11].) Thus, the encoded data signal is now filtered, isolated and then presented to the media converter, which is discussed next.

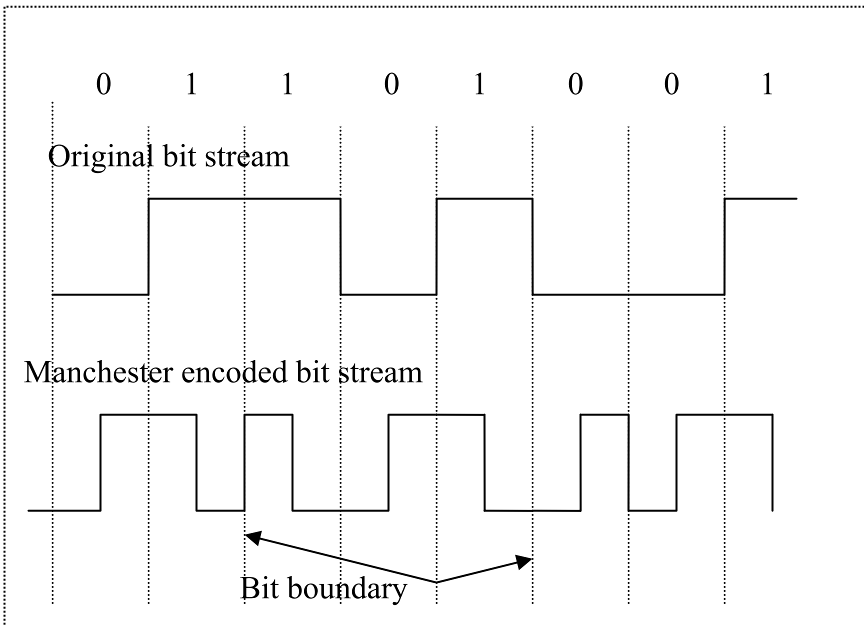

Figure 3. Manchester encoded bit stream 01101001. (After Ref. [11].)

b. Media Converter

The Media Converter (MC) could be thought of as the heart of the design. The MC receives the Manchester encoded signal described above and formats it into a useful form to modulate the laser beam. In addition the MC has to be able to sense and auto-negotiate the data transfer rate. Since Ethernet nodes essentially *communicate*, the media converter is required to send and receive data at either end. Thus the MC converts the received signals optical signals back to Manchester encoded Ethernet data as well. This process of conversions undertaken by the MC may not introduce any asynchronous delays between received and transmitted data as most Ethernet protocols are connection

based, i.e., data packets need to be acknowledged within milliseconds of receipt to avoid errors and connection resets. (See for example, Ref. [11].) Ideally, the MC makes the presence of the communicator in the communication channel transparent to the two nodes. Output of the MC has to be compatible with the type of signal expected by the laser driver. The laser diode driver chosen for this project accepts a signal form known as PECL or Positive Emitter Coupled Logic. Of the several signal schemes in wide use for high-speed data transmission interface betweens Integrated Circuits (ICs), PECL is the most common [12]. Other signal forms include LVDS (low-voltage differential signals), TTL (transistor-transistor logic), and CML (current mode logic) [12]. Since PECL uses a small swing in voltage to differentiate between logic levels and is able to use a positive power supply, it is ideally suited for serial or parallel transmission of data between ICs [12]. Indeed, whether the communicator interface is LVDS, CML or PECL was an early design decision that had to be made, as components are usually optimized/designed for a given type of signaling. The choice of PECL over other forms was one of the easier design decisions, due to the availability of a wide variety of low-cost PECL components. The output of the MC, a converted PECL signal, is next applied to the input of the laser diode driver, which will be discussed next.

c. Laser Transmitter

The laser transmitter consists of the laser driver and a laser diode. In order to convert the electrical signals that carry Ethernet data over copper wires to light signals that may be transmitted over free-space, it is necessary to modulate a laser beam to represent the data. The transmitter device used was a Laser Diode (LD), also referred to as a semiconductor laser. We opted to use an LD rather than a Light Emitting Diode (LED) due to several reasons. Chief among these was the higher modulation bandwidth of an LD, which enabled us to use a higher powered source at the desired bit rate. (See for example Ref. [1].)

A laser diode emits relatively high intensity light beam beyond a certain threshold input current through the device, which is intrinsic to a given diode for a given operating temperature T. Figure 4 depicts the two curves of light output of a typical laser diode versus input current at two different temperatures T_1 and T_2 (where $T_1 < T_2$). No-

tice that I_{th}, the threshold current is shifted right with the higher temperature. The threshold I_{th} as a function temperature is given by [13]

$$I_{th}(T) = I_0 + K_I e^{T/T_I} \quad (2.1)$$

where I_{th}, K_I, and T_I are specific to a given laser diode. Above this threshold, the optical power of the LD increases linearly as shown in Fig. 4.

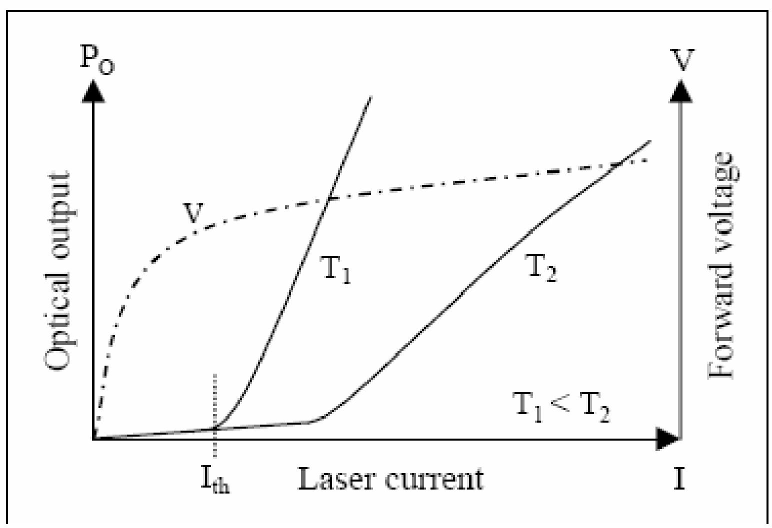

Figure 4. Optical output vs. input current of a typical laser diode. (From Ref. [13].)

Dependent on the slope of the curve of the optical output vs. input current, a small variation in the input current results in a larger change in the optical output of a laser diode [13]. This very useful property of the LD is commonly exploited to transmit data on the laser beam. The process works as follows. A biasing current maintains the LD slightly above or very close to the laser threshold. When a logic “1” is transmitted the bias current is increased momentarily. Similarly a “0” is transmitted by maintaining the *rest* current level or increasing input current just above rest state, yet not up to the point when it would be read as logic “1”.

There are several established modulating methods used in communication engineering today. Intensity Modulation (IM) was described in general terms above and

depicted in Fig. 5. Some other popular modulation schemes are Frequency Shift Keying (FSK), Amplitude Shift keying (ASK) and Phase Shift Keying (PSK). The intrinsic properties of each scheme determine its suitability for a given application. Intensity modulation, also known as On-Off-Keying (OOK) lends itself well to digital data modulation in optical networks. Most fiber optic data transfer technologies use OOK as their modulation scheme.

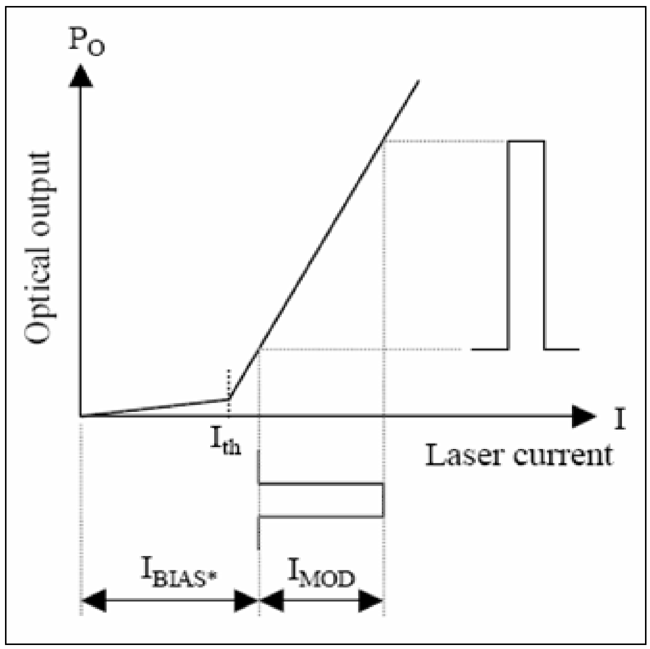

Figure 5. Intensity modulation of a Laser Diode. (From Ref. [13].)

The term Slope efficiency (*S*), describes the behavior of the slope with temperature. For a given LD, and a temperature *T*, the slope efficiency is given by [13]

$$S(T) = S_0 - K_s e^{T/T_s} \tag{2.2}$$

where S_0, K_S and T_S are specific to the laser diode. For efficient modulation, high slope efficiency is beneficial. Figure 6 shows the case of an LD that has diminished slope efficiency at a higher temperature T_2. Note that if we maintain the modulation current I_{Mod} constant with rising temperature, the modulated signal greatly decreases in amplitude. Figure 6 is deliberately exaggerated for clarity. It follows then, that the modulation pa-

rameters need to be dynamically adjusted with temperature, and/or any changes to $I_{th.}$ In order to successfully maintain an FSO data link, the LD driver needs to be sophisticated enough to track changes to threshold current and slope efficiency and adjust its bias and modulation current correspondingly [13]. Most high quality LDs have embedded monitor photodiodes that are designed to provide feed back to the driver. The LD driver uses this feedback current to track the output and change its parameters. For these reasons, the laser driver and the LD have to carefully match to optimize the performance of the FSO device [13]. There are several key parameters of the LD that have to be considered during the design process. Foremost among these are the wavelength (λ) and the optical power output (P_o) of the diode. Other parameters that need to be weighed are the rise and fall times (t_r and t_f), operating temperature and the parameters of the monitor photodiode. We will discuss these in greater detail next.

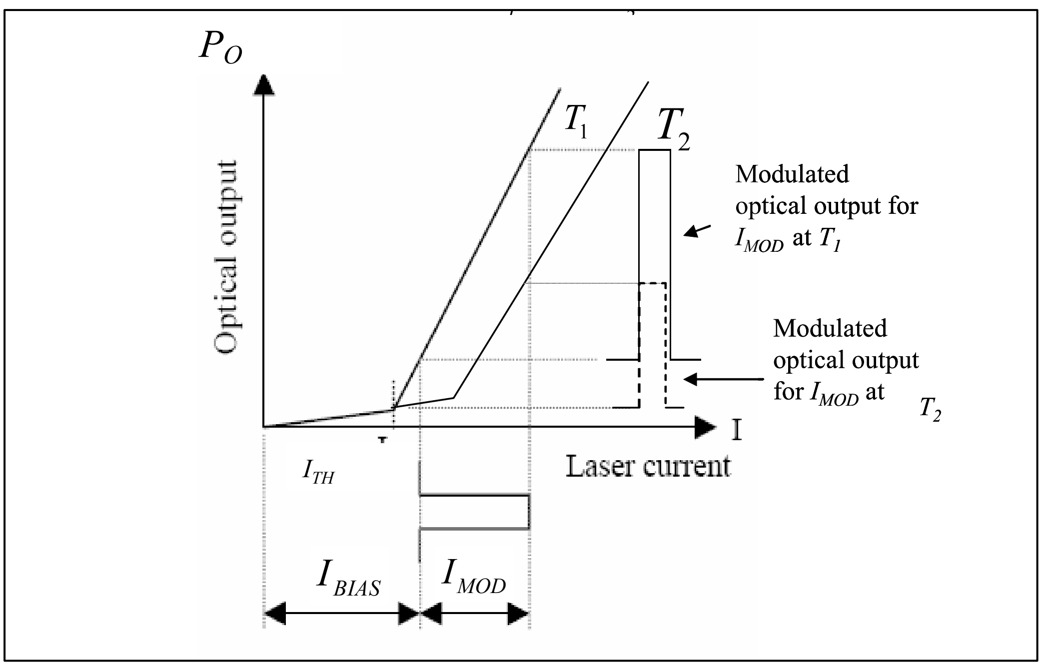

Figure 6. Modulation of a Laser Diode at two operating temperatures T1 and T2. (After Ref. [13].)

As we mentioned in the previous chapter, FSO technology is handicapped by atmospheric attenuation to a great degree. Some wavelengths are more susceptible to attenuation and scattering than others. (See, for example, Refs. [3, 14].) Figure 7 depicts

four graphs of the transmission vs. wavelength for a model transmission path of 1 km [14]. The topmost panel of the graph shows the theoretical absorption due to water vapor in the atmosphere alone, under foggy conditions with visibility at 200 meters. The *y*-axis ranges from a minimum transmission of zero (maximum absorption) to maximum transmission of one (minimum absorption.) Note that some wavelengths are affected more severely than others. Similarly, the second panel shows absorption due to atmospheric

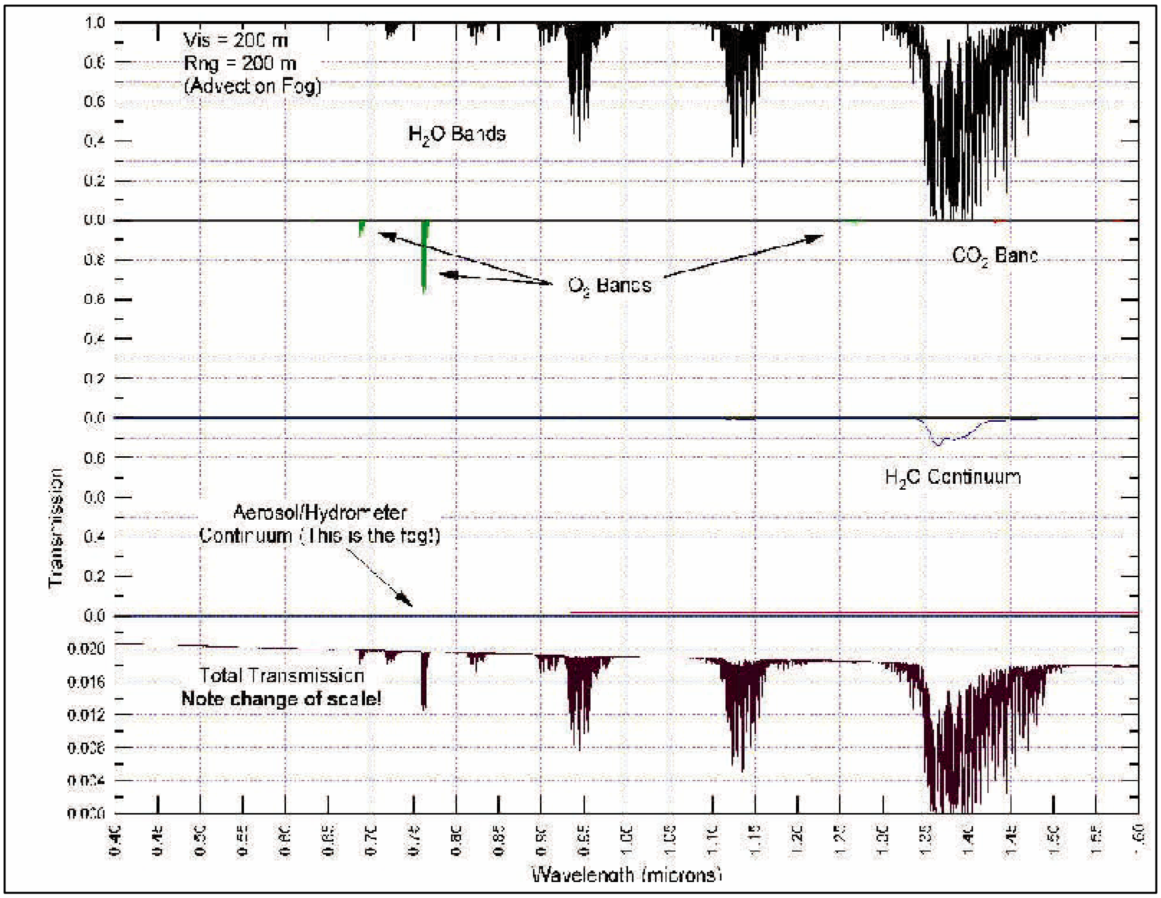

Figure 7. Atmospheric propagation. Transmission vs. wavelength. (From Ref. [14].)

oxygen and carbon dioxide for the same wavelengths. It can be seen that the effects are far less marked and confined to few narrow wavelength bands. The third panel shows the effects of Mie scattering due to fine water droplets that is advection fog. The entire spectrum of interest is significantly attenuated by the heavy fog. We may conclude that our FSO link will not be effective under these conditions. Finally the bottommost panel depicts the effects of all three forms of loss: absorption, Mie scattering, and molecular scat-

tering on one graph. The y-axis scale is changed for this graph. We see that there are certain wavelengths to be avoided in our selection of an LD [14]. In fact, due to the ubiquity of LDs of certain widely used wavelengths, the wavelength selection process becomes less daunting than it seems.

The optical power output of the diode is a critical design parameter as well. Indeed, the LD power, P_o, is one of few variables that a designer may control in the FSO link equation given below [14].

$$P_{received} = P_o \frac{A_{reciver}}{(\theta R)^2} \exp(-\alpha R) \tag{2.3}$$

where $P_{recived}$ is the power received at a distant point, P_0, is the power output of the transmitter, $A_{reciver}$ is the area of the receiver, θ is beam divergence in radiance, R is the range between the receiver and the transmitter, and α is the atmospheric attenuation coefficient. This equation is based on Beers's law which tells us that light traveling trough the atmosphere will attenuate as [5]:

$$I_R = I_o \exp(-\alpha R) \tag{2.4}$$

where I_R and I_O are intensities of received and transmitted light. The atmospheric attenuation constant α is obtained by summing together four components

$$\alpha = \alpha_m + \alpha_a + \beta_m + \beta_a \tag{2.5}$$

where α_m and α_a are molecular and aerosol scattering coefficients and β_m and β_a are molecular and aerosol absorption coefficients [Ref. 1, p. 49].

In Eq. 2.3, we have chosen to ignore the optical efficiency of both receiver and transmitter. Note that the power of the LD is one factor that can contribute to enhanced range. (Here we shall define range as the distance at which the least acceptable power is received by the detector.) However, due to safety concerns the output of a laser diode is a tightly controlled parameter. (The laser safety section of this thesis will treat this subject in more detail.) When α is significant, the exponential term dominates, and the received power decreases rapidly with distance. A greater output, under the right cir-

cumstances, could translate into longer range for the FSO system. However, due to safety and cost issues, the power output of the LD for this design is deliberately held low.

In addition to the wavelength and the power output, the rise and fall times of the LD need to be carefully chosen to accommodate the goal bit rate of Fast Ethernet, or 100 Mbps. Rise time refers to the time taken for the LD to increase its intensity from a 10% of the peak to 90% of the peak (some manufactures specify this value as the time to go from 20% to 80%.) Similarly, the fall time is the time required for the signal to fall from 90% of its peak to 10% of the peak. For fast Ethernet standards, we need rise fall times of the LD to be typically around 3 ns. (See, for example, Refs. [15, 16].)

Thus far we have covered the conversion process of Manchester-encoded Ethernet data to optical signals, and the laser driver and the diode which complete the process by transmitting the converted optical signals through free-space. To close the data link, we need to receive the optical signal at a distant point, interpret the modulated information or data, and convert these to electrical signals and finally to Manchester encoded data suitable for transmission on copper UTP cable. The next subsection introduces the receiver system that is the first step to this process.

d. Receiver

The receiver subsystem comprises of a photodiode, a transimpedance amplifier (TIA) and a limiting amplifier. Each of these components will be covered in general terms. Vital parameters for design will be discussed in sufficient detail to give the overall functionality of the receiver.

The optical detector is a device that responds to light intensity by producing an electrical current or voltage. Detectors vary widely in size, sensitivity to a particular wavelength of light, responsivity (a parameter defined as the amount of current or voltage produced in response to a 1 Watt of power at a given wavelength) and the material they are made of (which generally determines the sensitivity to a particular wavelength.) The most commonly used photodetectors for high speed communication applications are the Positive Intrinsic Negative (PIN) photodiodes. Another more costly, yet a higher performing alternative is the Avalanche Photo-Diode (APD.) An APD is more

sensitive than a PIN diodes and requires higher biasing voltages. (See, for example, Ref. [1].) Generally they are not used in small devices that have limited power supplies. The PIN diodes are made either with Silicon (Si) or other combinations of material such as the popular Indium-Gallium-Arsenide (InGaAs), which responds well in the IR and near-IR spectrums. (See, for example Ref. [1].) Silicon diodes are usually meant for the visible and near-IR portions of the spectrum.

The detector has to be fast enough to distinguish between ones and zeros in the optical signal received. Inadequate response will cause a condition referred to as Inter-Symbol Interference (ISI) where adjacent bits become indistinguishable. Inter-symbol interference can also be caused by excessive noise [17].

Recall that the variable $A_{receiver}$ in the FSO link equation (Eq. 2.3) refers to the size of the detector. This is important as a larger detector can capture more of the incident light on it. Beam divergence causes the effective radius of the light beam to increase as it travels longer distances. The effective radius is the distance from the center of the beam to a point where the intensity has diminished by a factor of $1/e$ [17]. It follows then that a lager detector can capture more of the laser beam at longer distances. Unfortunately in practice larger detectors cause unacceptably large RC time constants due to their larger internal capacitance. For high speed applications, it is unusual to find suitable detectors larger than 100 μm in diameter (see, for example, Refs. [17, 18].) Finally, the detector has to be sensitive enough to detect relatively low power signals. The minimum detectable power used for quantifying the sensitivity of a photodiode, is given in terms of dBm. A typical value for a fiber optic receiver is about -30 dBm. (See, for example, Ref. [14].) A receiver with this sensitivity would be able to detect a signal whose power has attenuated to a mere 1.9 μW. Another figure-of-merit used to evaluate the performance of a detector is the NEP (Noise Equivalent Power). Noise equivalent power is usually given in Watts (W) or mW, and is defined as the radiant power that produces a signal-to-noise ratio (SNR) of 1, for a given signaling rate, wavelength and noise bandwidth [19].

The transimpedance amplifier or the TIA receives the electrical current produced by the detector in response to a light signal. The output of the TIA is a differen-

tial voltage usually with a peak-to-peak swing less than one Volt. The TIA parameters of bandwidth and dynamic range are critical to the proper operation of the receiver system. The bandwidth of the amplifier is derived from its input resistance and capacitance. The dynamic range of the amplifier is the ratio of maximum input current to the peak noise current [17]. At first glance, the TIA appears to be no more than a low noise preamplifier. However, it does more than simply convert the detector output. (See, for example Ref. [20].) In actuality, the TIA is perhaps the most complex of the subsystems in the FSO communicator design. A multitude of factors can affect its operation. Such variables as the size of the feedback resistor, source capacitance, feedback capacitance, bandwidth, and desired gain, all interact to make the task of optimizing a TIA an extremely complex undertaking [20]. Fortunately, TIAs are available for purchase in packaged form for a given set of parameters. Due to size-related capacitance issues similar to those we discussed regarding detectors, TIAs come in extremely small packages as well. For high-speed applications the TIA is embedded in the detector to minimize transmission path lengths.

The output of the TIA is received at the final stage of the receiver system, the limiting amplifier. The function of the limiting amplifier is to quantize the differential voltage at its inputs to a form of signal that is clearly distinguishable as a data signal. Thus the limiting amplifier has to make a decision if the instantaneous value that is being sampled is indeed a one or a zero. Excessive noise at this stage leads to bit-errors. Additionally the limiting amplifier has a gain of about 50 to 65 dB. (See, for example, Refs. [22, 23]. It is required to amplify a differential signal that could be as low in amplitude as 2 mV peak-to-peak to a TTL or PECL voltage (usually Vcc – 2V.) The typical limiting amplifier consists of several internal gain stages and is designed to minimize noise, delays and internal capacitance compatible with PECL, CML, TTL or a combination of these signaling schemes. Manufactures such as Philips Semiconductor and Maxim-Dallas make matched pairs of TIA and limiting amplifiers, usually for a desired bit rate, signaling scheme and voltage. (See for example Refs. [22-24].)

C. LASER SAFETY

We will briefly discuss laser safety as it applies to this project. Laser safety is a widely researched subject and the potential eye hazards from a laser beam are well understood. Laser classifications are regulated by an international body, the International Electro- Technical Commission (IEC) and, in the US, the Center for Devices and Radiological Health (CDRH), a part of the Food and Drug Administration. While the classifications used to differ slightly in their definitions according each body, they have been unified since 2001 [Ref. 1, pp 139-146]. There are two classes of lasers that we could have used during this project. These are IEC/CDRH Class I and Class IM. Since the project involved buying and using modular devices, the manufactures classification was adhered to and the required safety precautions taken during the testing. All devices used were rated as Class I laser products. Under this classification, a power density of up to 26 mW/cm^2 is safe for a 1500 nm laser. Since the project used 1310 nm lasers exclusively, the maximum safe power density would be somewhat lower. However the maximum power of any laser used during this research was under 5 mW at 1310 nm and the majority of the work was done with 0.3 to 1 mW rated devices. At 1500 nm, a Class I device has to be under 10 mW as measured with a power meter through a 7 mm aperture placed 14 mm away from the source. If using optics, the aperture size has to be 25 mm at 2000 mm from the source. The devices being used were well below these thresholds and no extraordinary precautions were therefore employed during this project. By definition, Class I lasers are "safe under reasonably foreseeable conditions for operations, including the use of optical instruments for intrabeam viewing" [Ref. 1, pg 141].

D. SUMMARY

In this chapter, the history of FSO which is believed to date back to the patent for the photophone was discussed along with the reasons for renewed interest in the technology. The major subsections of a theoretical FSO communicator, the copper media input/output system, the media converter system, the transmitter system and the receiver system were discussed with relevant theory behind each. Finally, laser safety issues were covered briefly as they pertain to the project. The following chapter covers the design and testing of the FSO device in detail.

III. DESIGN AND TESTING

In this chapter, the design and testing process will be covered in detail, with emphasis on design decisions on performance, and component selection criteria. We will discuss the reasoning behind the selection of main components and the problems encountered and the steps taken to overcome them.

A. SELECTION OF COMPONENTS

Even from cursory research into component parameters and prices at the inception of this project, it became very clear that the mass-produced components aimed at the fiber optic industry were freely available and inexpensive. That knowledge prompted an effort to keep the design parameters as close to existing fiber-optic standards as possible to minimize cost and supply delays during the research. As an example, consider the desired data rate, the Fast Ethernet standard of 100 Mbps. The Synchronous Optical Network Transport System (SONET) standard OC-3 is rated at 155 Mbps. (See, for example, Ref. [1].) Therefore any component meant for OC-3 devices conveniently exceeds the data rate standard we wish to meet. Similarly, there are two very common DC voltages used in the industry as the source voltages of ICs and other components such as LEDs and LDs, 3.3 V and 5 V. Our choice here was 5 V, due to this being the more popular choice at the moment for older OC-3 components, and hence the more economical one. The final design decision prior to the component selection step was to establish the signaling scheme between the options of PECL, ECL, and CML. Here PECL was an easy choice due to wider use, which again translates into lower cost and wide availability.

Thus having determined the design data rate, power-supply voltage, and the signaling scheme, the next logical step was to select a media converter that fell within those parameters. Indeed, the plan was to build the FSO communicator around the chosen media converter IC.

1. The Media Converter

The media converters considered were from well known manufactures, and price and availability narrowed the list down to a few, which were closely looked at. Of these, the Micro Linear ML6652 media converter chip was finally chosen as it had excellent

support documentation, a competitive price, and application notes that included a recommended circuit for a media converter from copper to fiber-based Fast Ethernet (100BaseFX.) This circuit, shown in Fig. 8, could be easily tailored to suit our goal. Additionally, the ML6652 has an auto-negotiation feature that senses the data speed and steps between two rates, 10 and 100 Mbps [25].

The original approach was to build the entire device on a protoboard. This task was undertaken with misgivings, given the vulnerability to noise, interference and parasitic capacitance of the board for a system expected to operate at roughly 100 MHz. The author visited the manufacturer's design facilities in San Jose to confer with an engineer on the design team of the ML6652 media converter, and was shown a reference design kit that was developed by the company based on the recommended circuit in Fig. 8 for fiber optics-based communication links. The author was given a demonstration of the performance of the reference design (ML6652RDK) at the Micro Linear lab and realized that this pre-fabricated device could be modified to fit the basic prototype that was being considered. An obvious advantage was that the reference design was already tested and optimized to work as a media converter between fiber and copper.

Figure 9 shows the ML6652RDK as offered by Micro Linear Corporation. The rectangular device reference designated "A" is a fiber-optic transceiver. It is a modular component with an embedded Transmitter Optical Sub-Assembly (TOSA) and a Receiver Optical Sub-Assembly (ROSA.) The terms TOSA and ROSA are used to indicate modular integrated components, such as the TIA and detector in one assembly in the case of the receiver, and the diode driver and LD or LED in one assembly in the transmitter. The transceiver shown in Fig. 9 is a low-power device made by Agilent Technologies. It is equipped to accept two fiber optic cables, one each for receive and transmit. The transmit cable of one device needs to be connected to the receiver of the other, and vice versa. This device is connected to the rest of the circuit via an industry standard pin-out scheme known as 1X9. The ML6652 integrated circuit is indicated by the reference designator "B", is while "C" indicates the female RJ45 connector that would accept the incoming copper UTP cable. Figure 10 shows a typical application for the media converter.

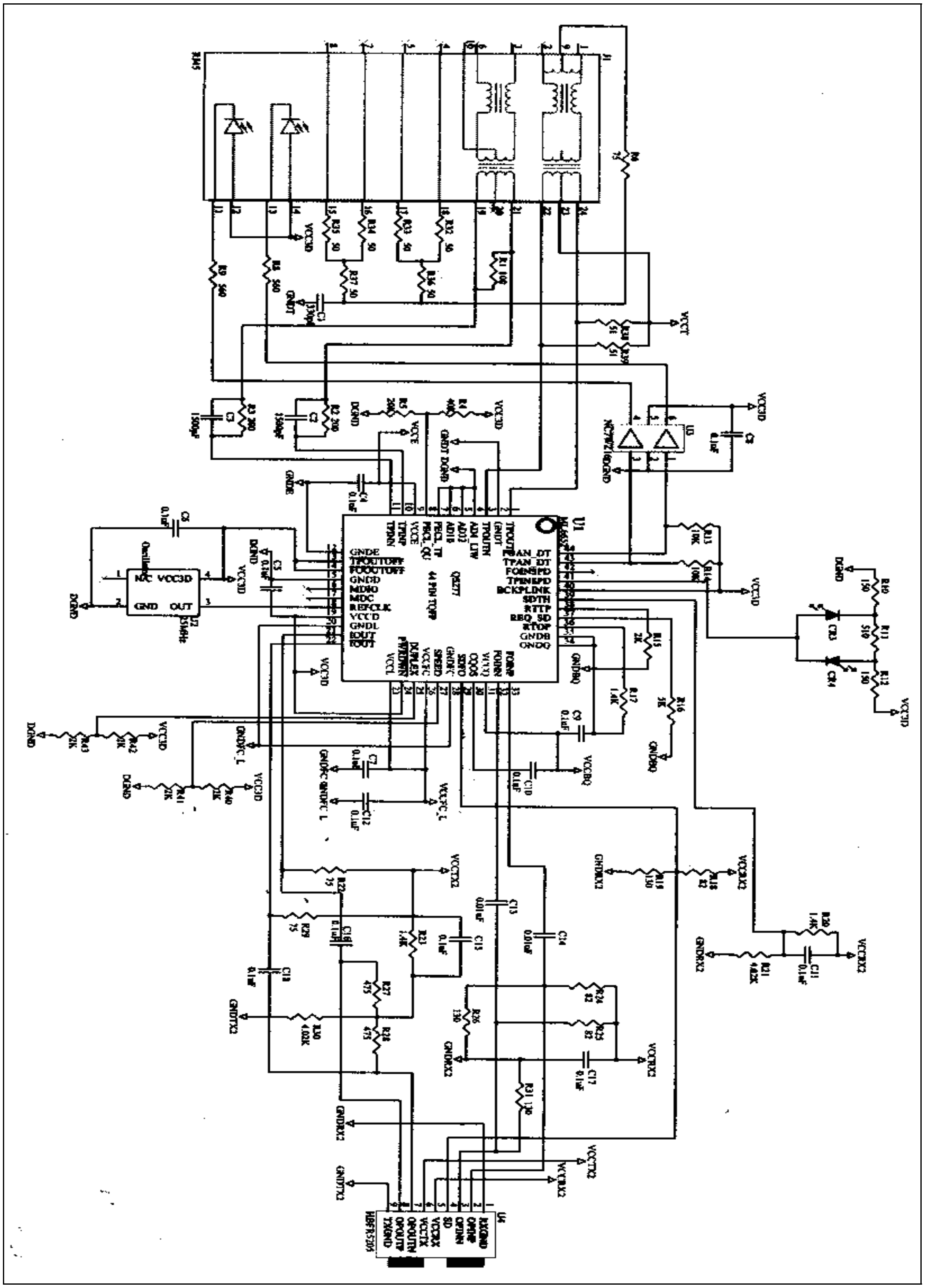

Figure 8. Manufacturer’s recommended schematic for a media converter between 100BaseTX (copper) and 100BaseFX (fiber) based on the ML6652. (From Ref. 26].)

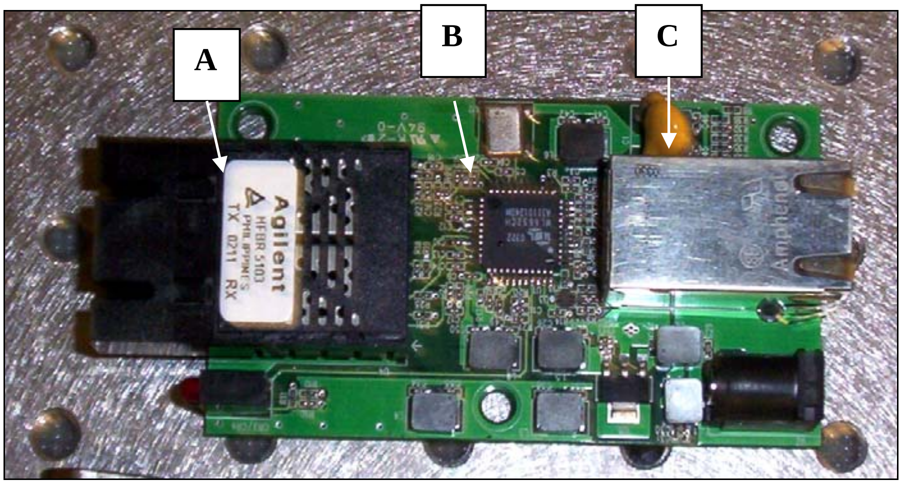

Figure 9. Micro Linear reference design device for the ML6652 media converter

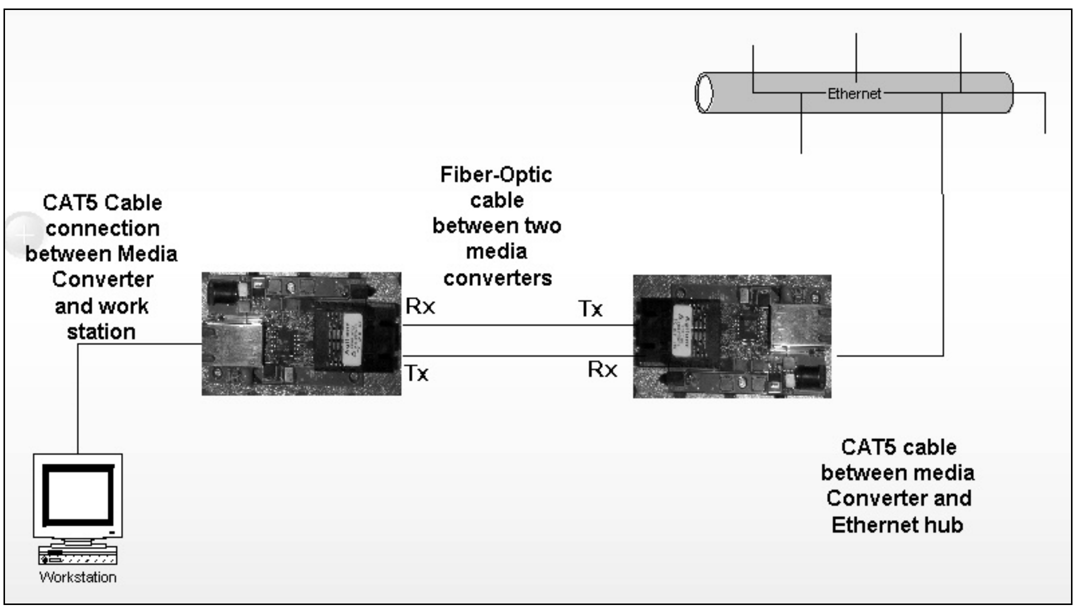

Figure 10. Typical application of a copper to fiber Media Converter.

Standard Cat-5 UTP cable connects an Ethernet hub to the media converter, which converts the electrical signals to optical signals, and transmits these optical signals via fiber optic cable to another media converter. Here the process is reversed, and the light signals are converted back to electrical signals, and transmitted via UTP cable to a

workstation, hub or a router. Note that this scheme may also be used to connect two workstations in a peer- to-peer network, or a networked printer to a hub. The most common application for the type of media converter described above is to extend the range of a LAN beyond the range limitations of UTP cable.

In the introductory chapter it was stated that the premise of this thesis was that a low-cost man-portable FSO device could be designed to take the place of fiber under some circumstance. In essence, this proposed device would have all the characteristics of the link shown in Fig. 10, sans the fiber cable. Hence one of the design strategies was to find a way to practically modify this functional media converter circuit to suit our goals.

The other approach was to build discrete subsystems and use the media converter as the processor of the device. We attempted the latter during the initial stages of the project, to explore the feasibility of assembling the subsystem using discrete components on a protoboard as described in the following sections.

2. Copper Input/Output System

The Copper Input/Output system was the least complicated design of the entire project. The system comprises of a two transformers, a few capacitors for filtering noise, and a female RJ-45 connector. The transformers are freely available and very inexpensive. The decision was made to purchase a device manufactured by Pulse Inc, model H1012, which is an integrated circuit containing two transformers. Note that the transformers simply isolate the network from devices that plug-in to it. (See Chapter II.B.1.a.) The manufacturer's recommended circuit was used to build the device on a proto-board. This circuit is shown in Fig. 11 [27]. Testing of the circuit was a trivial process, consisting of observing input and output on an oscilloscope and verifying that a 150-MHz square wave input on pins 3 and 6 of the RJ-45 connector were reproduced on pins Tx+ and Tx-, and that the same wave form input on pins Rx+ and Rx – could be seen on pins 1and 2.

3. Laser Diode Driver Circuit

In the previous chapter we discussed the important parameters of an LD and the LD driver. The search for a suitable driver started with querying major manufacturers

such as Micrel, Philips Semiconductor and Maxim-Dallas. The device ultimately chosen was a Maxim3263 integrated LD driver. It was competitively priced, had excellent support and was available for purchase in small quantities. This last criterion was sometimes a critical issue, when suppliers refused to sell small quantities of an item and samples were not offered by the manufacturer. The MAX3263 is rated at 155 Mbps, PECL compatible and needs a +5-V supply source. Some of the driver's parameters are programmable using external resistors and capacitors. The circuit recommended by the manufacturer is shown in Fig. 12 [28]. This circuit was built on a proto-board as depicted on Fig. 13, and tested on an oscilloscope with a simulated PECL input signal. As shown on Fig. 14, the output waveform was noisy and somewhat distorted. It did however, seem to follow the input waveform closely. The diminished amplitude of the output is due to the 50 Ω load placed on the output to simulate the actual LD. The noise and the ringing could be attributed to the poor noise immunity offered by the protoboard at the desired frequencies.

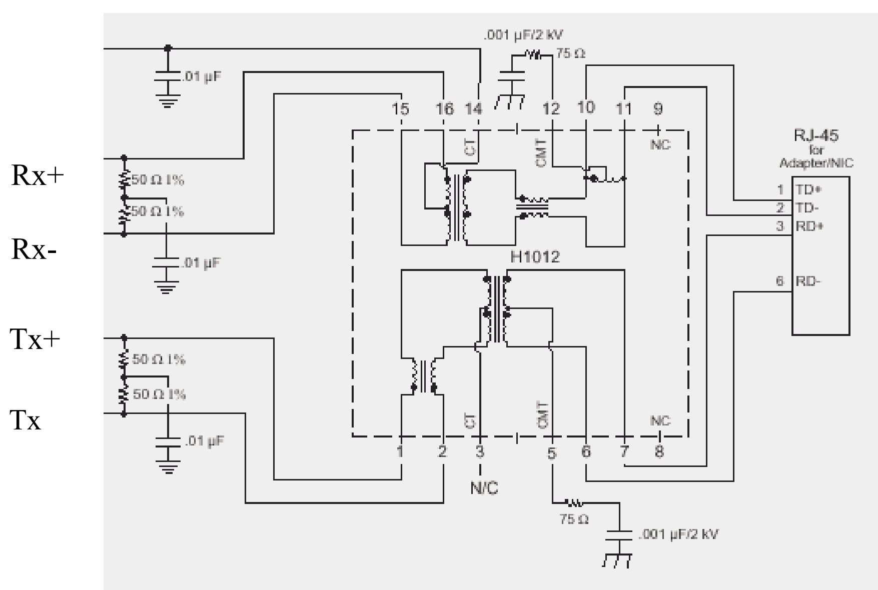

Figure 11. Proposed schematic for the copper input/output system. (After Ref. [27].)

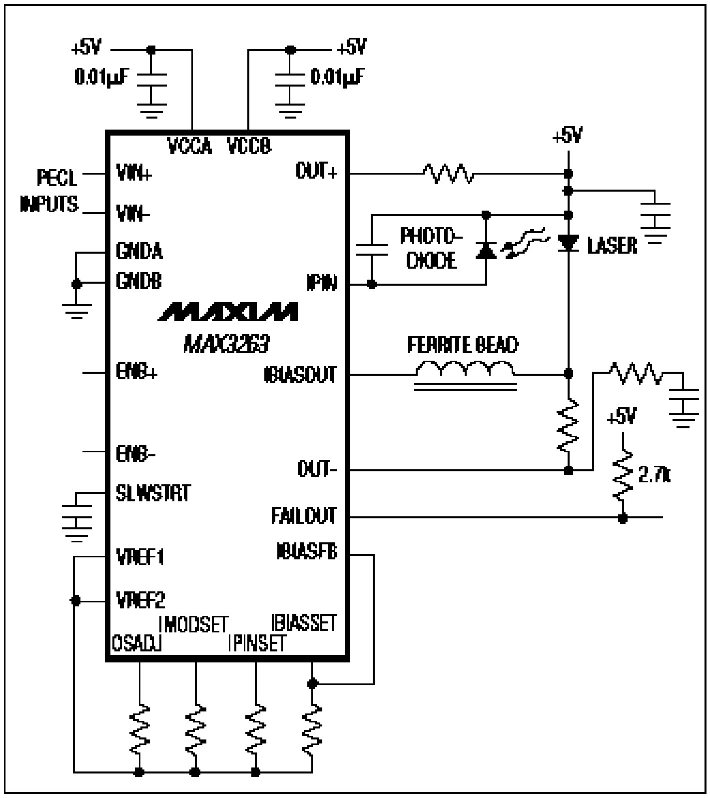

Figure 12. Recommended schematic for a driver based on the MAX3263 integrated circuit. (From Ref. [28].)

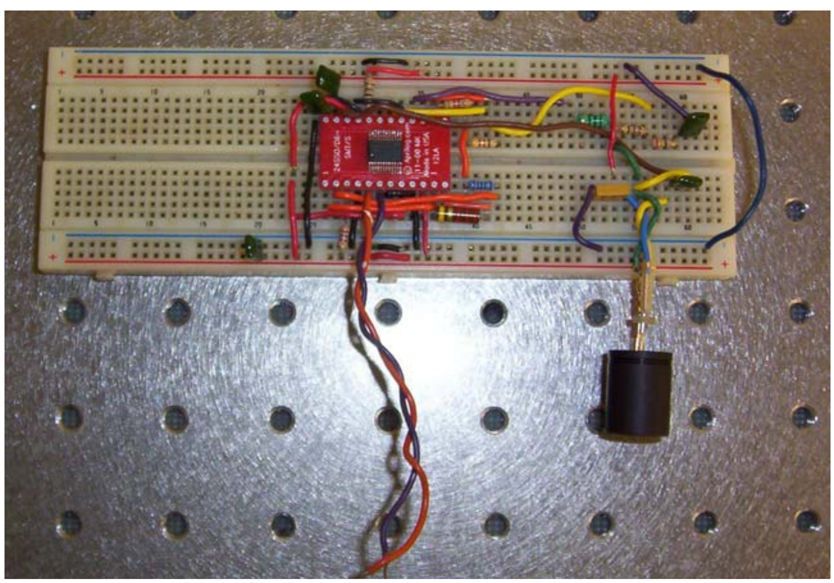

Figure 13. Proto-board implementation of diode driver circuit.

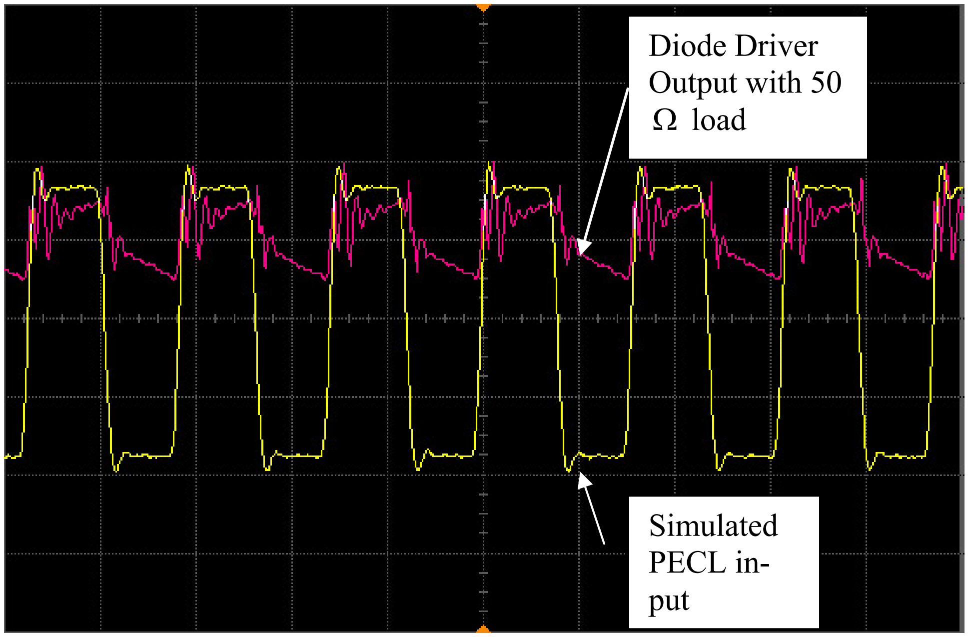

Figure 14. Oscilloscope output for LD driver simulation at 150 MHz.

4. Receiver System

The receiver proved to be the most difficult to build. Having gone through the same selection process as with other components, it was decided to use a TIA and limiting amplifier pair (see previous chapter for a complete discussion on TIAs and limiting amplifiers) manufactured by Phillips Semiconductor Corporation. These were the NE5211 TIA and the NE5217 limiting amplifier. One of the unanticipated difficulties encountered during this stage was the diminutive size of components. As discussed previously, TIAs and even limiting amplifiers are manufactured relatively small to avoid some performance impeding effects of size related capacitance. During the selection process it was evident that some of the components that were otherwise suitable for the application were too small to handle without specialized equipment. This was especially true of TIAs. The two components finally selected did not have the best parameters. In fact, the signaling used by the Phillips components was TTL rather than PECL, forcing the use of a TTL-to-PECL converter between the output and the media converter. The two components were recommended to be used together by the manufacturer in the circuit shown in Fig. 15 [21]. The signal conversion was accomplished with a Fairchild Semiconductors 00391 TTL-to-PECL translator. This circuit proved to be unworkable

due to excessive oscillations and noise. It became clear that a detector with an embedded TIA was necessary to overcome noise.

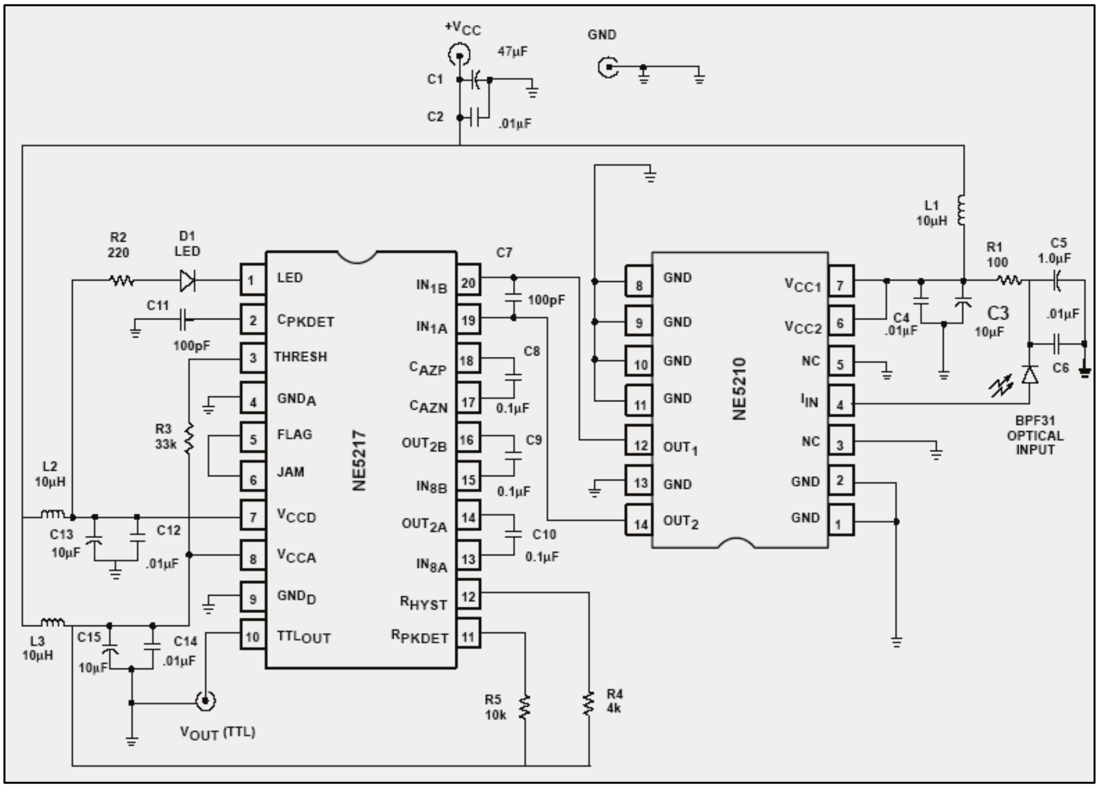

Figure 15. Receiver circuit based on Philips Semiconductor parts NE5217 and NE5210. (From Ref. [19].)

B. USE OF THE MEDIA CONVERTER REFERENCE DESIGN KIT

1. Modifications to the ML6652RDK

The above results were not encouraging as it was evident that noise and the problems caused by diminutive components were formidable obstacles to building a testable prototype. It was decided to try a new approach using commercially available media converter design kits originally fabrication for fiber links. Two ML6652RDK media converter reference design kits (see Section A.1) were purchased with the aim of modifying them to transmit and receive over free-space rather than over their intended medium, i.e., fiber-optic cable. The transceiver modules were equipped with SC-type connectors. These SC connectors surrounded an LED in the case of the transmitter side of the trans-

ceiver or a photodiode in the case of the receiver side. On the test bench, a computer was setup as depicted on Fig. 10. The UTP cable from one of the media converters was connected to an Ethernet port in the laboratory, while the other led to a laptop computer configured to be on the NPS network.

Figure 16 shows the actual setup with fiber optic cables connecting the two devices. The device on the left is connected to a wall port and the one on the right is connected to a laptop computer. The system worked as expected, at 100 Mbps according to the connection properties, and normal browsing, email and other network services all functioned normally. Thus the baseline for performance was set as normal Ethernet functionality, at 100 Mbps from a standard wall port. The next step was to attempt FSO transmission at extremely close range, to see if the transmitter (the LED in the Agilent device) was able to send data over free-space to a receiver a few centimeters in front of it.

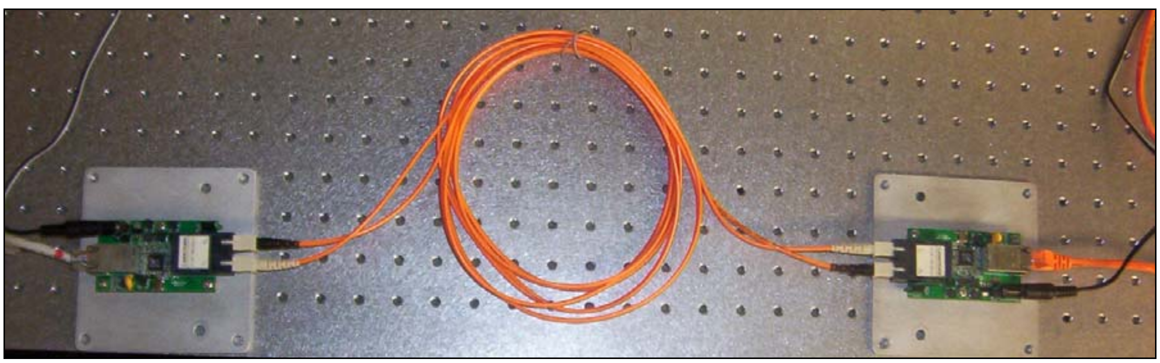

Figure 16. Two ML6652RDK devices linked with fiber optic cables.

The two media converters were lined up as shown in Fig. 17 and powered up. This did not have the expected results, even when the two devices were mated against each other. This should have worked in theory, as the setup worked when fiber was connecting the Tx and Rx of each device. When the fiber is connected as shown in Fig. 16, the tip of the fiber is held a few micrometers in front of an LED by the pre-aligned SC connector, at a point where vast majority of the LED's power would transfer into the fiber. The light then travels through the fiber and emits out the other end, which is again held a predetermined, microscopic distance away from a photo-detector by another SC connector. In order for the setup depicted in Fig. 17 to work, the following had to hold true:

1. The light beam emitted from the transmitter is sufficiently collimated, i.e., able to focus sufficient power to be detected by the receiver that is placed in front of it.
2. The receiver sensitivity is sufficient to detect the beam emitted by the transmitter.
3. The alignment between the receiver/transmitter pair is true.
4. That the above conditions are true for both paths.

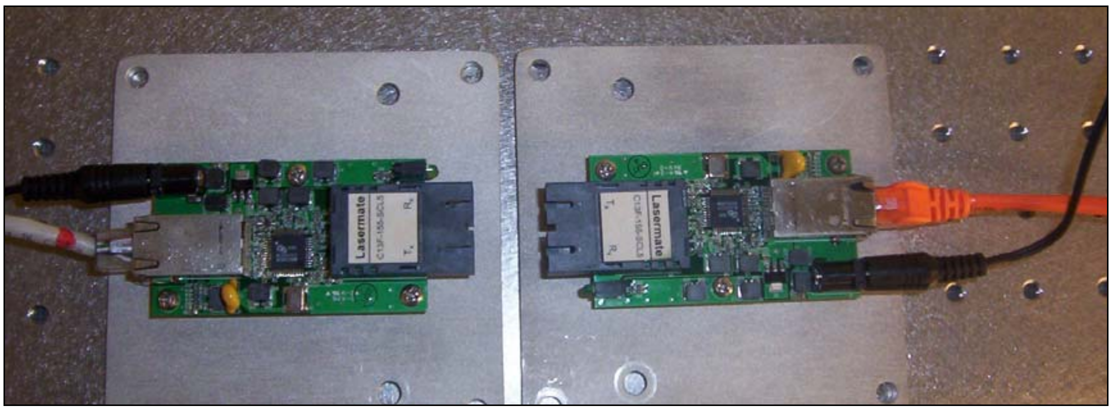

Figure 17. Initial attempt at FSO. Two ML6652 devices shown aligned receiver to transmitter.

Note that the ML6652RDK is equipped with an Agilent HFBR-5103 transceiver module as shown in Figs. 16 and 17. This unit operates at a wavelength of 1300 nm and is rated at a maximum power output of –14 dBm or about 0.04 mW [16]. The failure of the experiment was thought to be due to the very low power output of the LED. Hence it was decided to replace the entire transceiver module with a higher powered LD-based unit. The plan was to remove the modular 1x9 pin device carefully and solder in a 1x9 socket, enabling us to plug-in experimental devices, or easily access the output /input data lines of the media converter IC. Figure 18 shows the ML6652RDK after the transceiver module had been removed and the socket soldered on. The 1x9 pin transceiver is a common component and comes in a variety of power levels and qualities. The pinout of the 1x9 module is given in Table 1. At this point various transceiver models were considered as a replacement. The transceiver had to be equipped with an LD rather than an

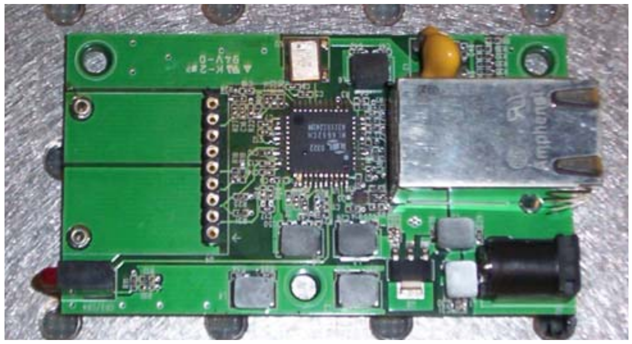

Figure 18. The ML6652RDK with the transceiver module removed and a 1x9 pin socket added for quick module change.

Pin number	**Designation**
1	Vee(receiver)
2	Receive data +
3	Receive data -
4	Signal Detect
5	Vcc(receiver)
6	Vcc(transmitter)
7	Transmit data -
8	Transmit data +
9	Vee(transmitter)

Table 1. Pinout of the 1x9 transceiver module. Note that pin number 1 is shown at the bottom of Fig. 18.

LED to test the hypothesis that an LD had a sufficiently cohesive beam to reach a receiver few centimeters away from it. Preferably a device with an output power of about 5mW would best suit the testing we had planned. It was found that the highest powered COTS 1x9 transceivers were made with a maximum power of around 1mW and most had

an average power rating of around –5 dBm or 0.3mW. The device ultimately chosen (for availability as much as for matching specs) was a manufactured by Lasermate Inc. Its absolute maximum power was 0 dBm (1mW) and the typical output was expected to be around −3 dBm (0.5 mW.) Two devices were purchased and the testing begun.As a first step, the setup shown in Fig. 16 was established, complete with fiber optic cable to ensure that the ML6652RDKs did function with the modifications, i.e., with the plugged-in transceivers rather than those originally built-in to the devices. The system worked perfectly, reporting a 100-Mbps connection (according to the speed of connection reported by the Windows tray icon for LAN connection) when the devices were powered up.

At this stage we sought to establish a benchmark to compare with future results. A shared folder was created on a desktop computer that was connected to the NPS network via the traditional means, i.e., a UTP cable to a wall Ethernet port. Using a laptop also connected to the NPS network, by the same means, a very large file (151MB) was transferred to the shared folder from the laptop. This transfer was timed and repeated three more times, so an average time may be obtained for the transfer over a conventional LAN connection. This procedure was repeated for a 12.1-MB pdf file and a 6.87-MB doc file. These files were deliberately chosen to be larger than what we typically deal with, in order to lengthen transfer times (for more accurate time measurements) and to detect any intermittent discontinuities in the link when the tests are repeated for the FSO link. Next, the same files were transferred with the laptop now connected as seen on Figs. 10 and 16 through the fiber connection.

Having thus established a baseline set of data on desired data speeds, the fiber optic cables were removed and the two modified ML6652 devices were lined up as shown on Fig. 17. This produced the hoped-for results. The link lights on the devices and the Windows tray icon on the laptop confirmed a 100-Mbps connection over free-space, albeit just 5-mm of free-pace. This distance could be extended to 4 inches before the link failed. This result confirmed that the basic circuitry and the concept were sound, and that a low-power device could be used to pass data over free-space.

As encouraging as these results were, without spanning greater distances the premise that a small FSO device could be used in military applications was a long way

from being proven. Now the work began in earnest to establish a longer link. It should be noted that the diameter of the receiver (photodiode) in a 1x9 transceiver is roughly 75 μm. (See for example, Refs. [15,16].) In essence, when we place a receiver this size in the path of a uncollimated laser beam, we are hoping to capture only a small percentage of the power of the laser. It follows then that we need a larger receiver or very finely collimated laser beam to get better performance.

The two ML6652RDK devices were carefully separated while maintaining alignment to ascertain the spatial limits of the link. It was established that the link could not be maintained beyond roughly 6 cm of separation (from transceiver edge to transceiver edge.) The LD, while emitting reasonable power (we know this from the specs) was not emitting a collimated beam. This was confirmed by placing a graph paper 10 cm in front of the transceiver and using an IR viewer to ascertain the size of the beam. This experiment showed that the beam spread widely with distance, as expected. The beam measured roughly 10~12 cm in diameter at just 10 cm away from the transceiver edge, and continued to spread with increased distance. This was not unexpected. The transceiver is designed to accept a multimode or single-mode fiber. As designed, it requires neither collection optics on the receiver, nor beam-shaping optics on the transmitter to function as intended. In order to successfully design a FSO device with these transceivers, some means of incorporating optics into the design had to be discovered. Before progressing further, some data on file transfer rates was collected, as outlined above, with the FSO link at its maximum possible separation. This data is discussed in Chapter IV.

Given the compact design of the transceiver, there was no straightforward means of using optics to achieve efficient collimation and collection. As this required significant structural engineering, another approach was considered. This method called for a collimation lens connected to a fiber optic cable to be used to collimate the laser beam, and another collimation lens, again coupled to a fiber, be used to receive the collimated beam. The collimation lenses had to be specialized for a given wavelength, and precisely manufactured to efficiently couple most of the light back and forth from the miniscule fiber tip. Suitable lenses were located and purchased to conduct the next phase of the experiment.

Three sets of collimation lenses were tested. They were of focal lengths 15.2 mm, 11.4 mm and 4.5 mm. The lens specifications claimed beam diameters of 6.2 mm, 2.74 mm and 3.8 mm respectively for the above focal lengths. Lenses could be connected to a fiber optic cable via an FC type connector. In theory, the collimator is designed so that, when the fiber is seated in the housing, the fiber tip is precisely at the focus of the lens as shown on Fig. 19 [29].

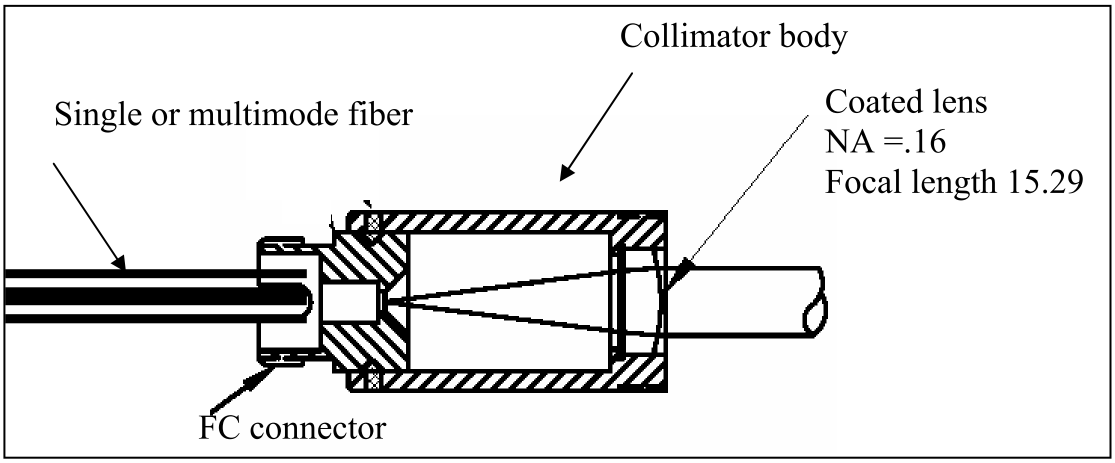

Figure 19. Schematics of 15.29-mm fiber collimation lens. (After Ref. [29].)

In order to facilitate testing various combinations of lenses, the setup shown in Fig. 20 was used. Note that one leg of the Tx-Rx path was connected via fiber to avoid having to perfectly align both paths during the testing stage. The rational here was that if linking could be successfully achieved via a certain combination of lenses for one path, it could be later adopted for both. During testing of optics, the one fiber path served to reduce the variables that could prevent a successful link. With the setup as shown in Fig. 20, the collimation of the beam was confirmed with an IR viewer. It was observed that contrary to the manufacturer’s claim of perfect mating of the fiber with the focus of the collimating lens, much manipulation of the fiber connecter was required to get the optimal collimation (as observed by the IR viewer and a makeshift power meter.) This proved to be more of a challenge when attempting to couple the free-space beam back on to the fiber. With a single-mode fiber connected to the receiving optics, this task was found to be too time consuming. In order for the link to work, i.e., sufficient power of

the beam to be harnessed into the tip of the fiber, the fiber tip had to be placed at the very focus of the lens with very little tolerance in any dimension x, y, or z. When a multimode (62.5 µm) fiber was used, the focusing was found to be easier.

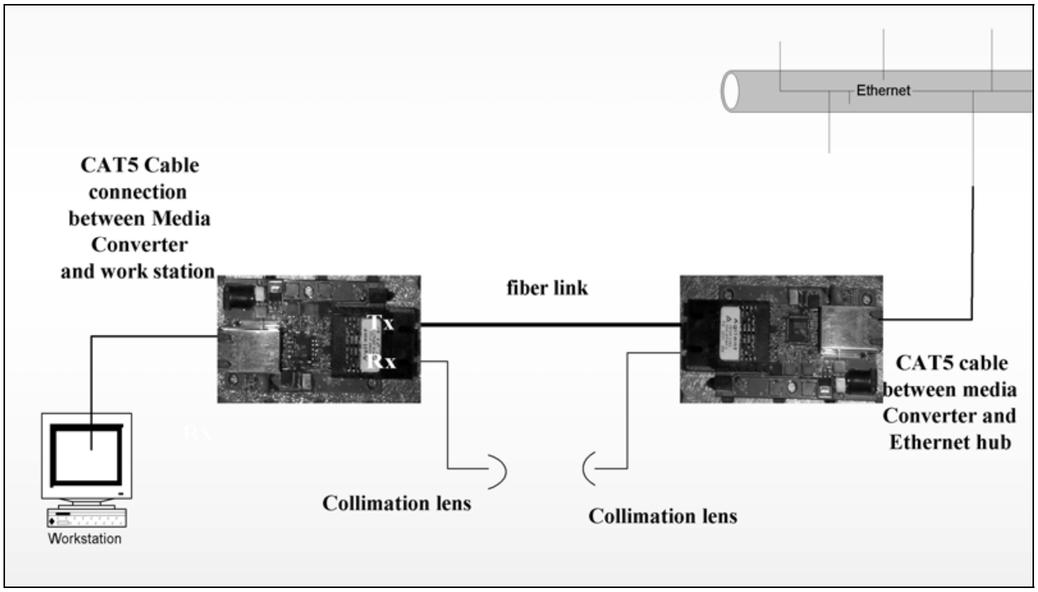

Figure 20. Two media converters setup with one fiber link and a free-space link through collimation lenses.

A link was established at a distance of 60 inches on the optical bench. The laptop computer connected to the NPS network via the FSO link reported a 100-Mbps connection, and was able to browse the internet, transfer files and have all the normal functionality of a computer connected via traditional means. At this point, the fiber optic cable that linked the second Tx-Rx leg was disconnected and replaced with an FSO link identical to the first link. Again the beam alignment was exceedingly time consuming and difficult. Normal network functionality was observed once both beams were aligned, with the computer reporting 100-Mbps connection. The file transfer test was conducted again. Figure 21 shows one of the ML6652 devices with both receive and transmit lenses connected. Although a fully functional FSO link was established over a distance of 5 ft, it was on an optical bench, with anchored lenses and under laboratory conditions. Given the difficulty to align the receiver end of the beam, we could hardly call this a workable

solution. However, it was a significant result in that it supported the hypothesis that the link distance could be extended with optics, and that a small device could manage to establish an FSO link at the Fast Ethernet data rate of 100 Mbps. Also encouraging was the fact that the transmitted beam was stable and maintained its collimation. This meant that at the transmitter end at least, the collimation lenses were useful. At this point it was obvious that using a small collimation lens was not a practical way to *collect* the light beam and focus it on the receiver.

An encouraging discovery was made at this point, enabling further progress. While looking at means to solve the limitation posed by the fiber-connected receiver, it was discovered that collimated beam could be shined directly at the transceivers' miniscule detector and a link could be established. Note that the detector diameter is roughly 75 µm and it is designed to accept a fiber connecter a microscopic distance away from it. It was further discovered that establishing a link in this fashion was drastically simpler than what was attempted previously. The effort to extend the link length beyond the optical bench length had to be suspended due to time constraints.

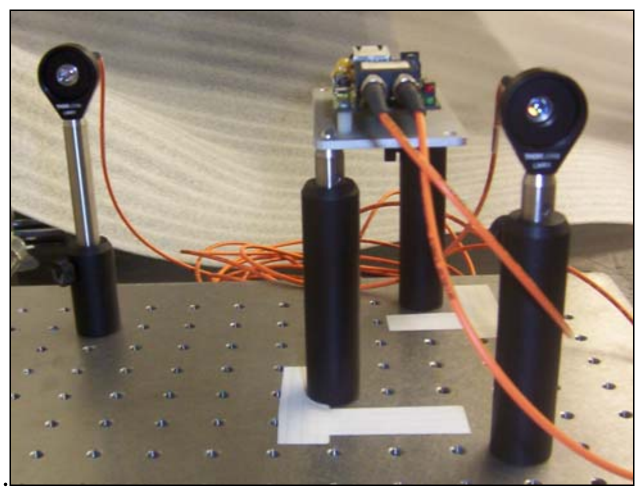

Figure 21. Collimation lenses shown connected to the ML6652RDK. One on left connected to the transmitter and the one on right is connected to the receiver.

As a final step, one of the transceivers with a collimating lens coupled to it was mounted on a tripod and powered up. Using an IR scope and a graph paper the beam size at 50 feet was determined to be well collimated and less than 8 mm in diameter. A veri-

fication of a longer distance was not possible due to the limitations of the IR scope. The scope needed near total darkness to view the 1310 nm beam due to the wavelength being near the high end of its detection envelop. Using the same setup and a detector coupled to a digital voltmeter, the voltage induced by the collimated beam was measured as a function of distance next. This was accomplished with the detector mounted on a second tripod which permitted movement along all three axes. This test was conducted along the basement corridor of Spanagel Hall late at night to avoid interference with regular business of the day. Since the transmitter in use was classified as a Class I device, no extraordinary safety precautions were taken. First the two tripods, pictured in Fig. 22, were aligned at a distance of 10 ft apart. Constantly observing the voltmeter output, the tripod axes were adjusted to obtain the highest possible value on the digital voltmeter, indicating that the detector was intercepting the central portion of the laser beam. This voltage was recorded as a baseline value. Next, a collection lens was placed on the detector, very nearly a focal length away from the detector. This was a plano-convex lens with a 25.4 mm diameter and a focal length of 25.4 mm. Another measurement was obtained, and this was recorded as a baseline value, with collection optics. With the transmitter stationary on one end of the corridor, the tripod was moved down in 20-ft increments. At each step the detector was carefully adjusted to obtain the highest possible value. Two readings were taken at each site, with and without the collection optics. The last measurement was taken at 300 ft away from the transmitter. The results are discussed in the next chapter.

C. SUMMARY

In this chapter, the design decisions were discussed for each subsystem. The prototype design steps were outlined along with results. Some protoboard designs did not function as expected and this was thought to be due to unacceptable noise and parasitic capacitance. After the modification of a reference design circuit was found to work, we tried to improve the performance of the prototype communicator by the use of optics. This was only partially successful as it was discovered that the collection optics coupled into fiber were extremely hard to align properly. Subsequently it was discovered that we could simply aim the beam into the connection socket that is meant for the fiber optic cable of the transceiver, to establish an FSO link. This method was significantly easier than

with a collimation lens attached to the receiver. An FSO link was established and tested on the optical bench with various combinations of lens. Finally, a power detection test was conducted up to 300 ft from the 1-mW transmitter.

The final chapter discusses the results we have obtained and the possible directions for further research.

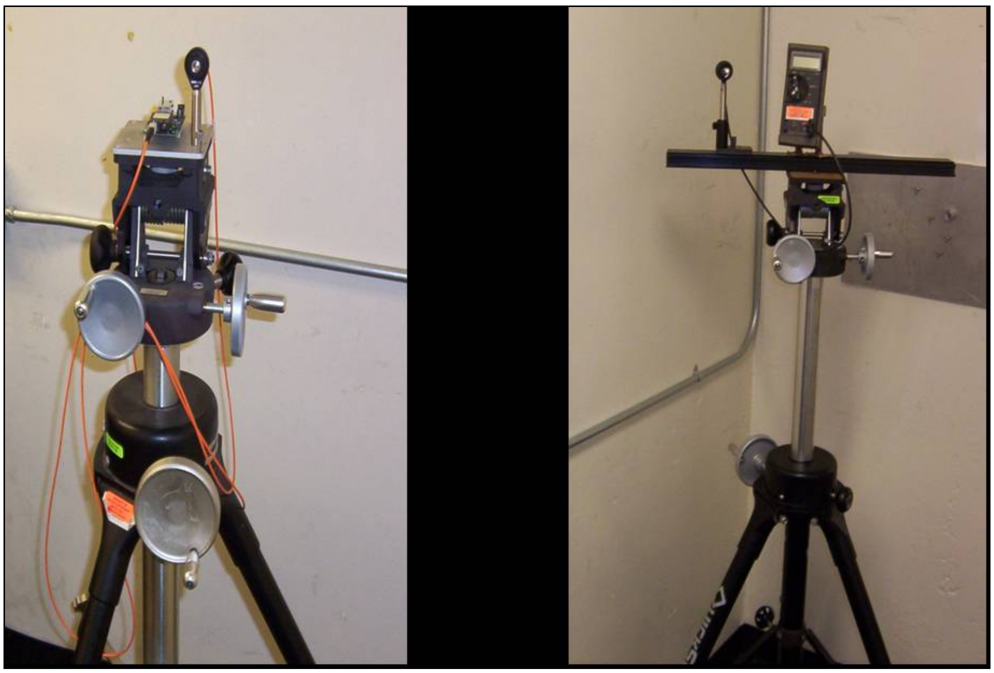

Figure 22. Tripod-mounted transmitter (Left) and photodetector with DVM (Right)

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IV. RESULTS AND CONCLUSIONS

This final chapter discusses the results we obtained during the testing phase. The conclusions we may reach, based on these results, and recommendations for further research are also presented.

A. RESULTS

The data transfer rates obtained by timing the transfer of two very large files and a smaller doc file are shown in Fig. 23. These data were collected during various phases of testing. The data collection procedure was outlined on Page 31. It should be noted that this was not a precise measure of the data rate over any connection, as the transfer time includes data buffering delays, network traffic routing delays, and the delays caused by the reading and writing latencies of the disk drives. However, this method would suffice to eventually reach a conclusion on whether the fiber connection or the FSO connection introduces discernible delays to Ethernet connections, given that test conditions remain reasonably similar. To this end, we would use the same two computers and identical files on the planned data collections. The uncontrollable variable was the wide, but random variations in network speed over a period of time. This is usually caused by instantaneous network traffic, or usage. In order to limit the effect of this phenomenon, the tests were done on a holiday. For the 151-MB zip file, the difference between the average transfer speeds was measured to be less than two seconds. The largest disparity in transfer rates was measured to be roughly three seconds for a data transfer of 12.7 MB (for the pdf file.) There was no appreciable difference among transfer rates for the smaller doc file either. For another estimate of the connection speeds, a software program that provided the instantaneous connection speed was used. This program reported instantaneous values of roughly the same speeds for all three types of connections over a long period of time. There was no user discernible change in internet browsing speeds between the three types of links. Above tests and long term observation of the FSO link led to the conclusion that a copper-FSO or copper-fiber media conversion does not add any measurable latency to network links.

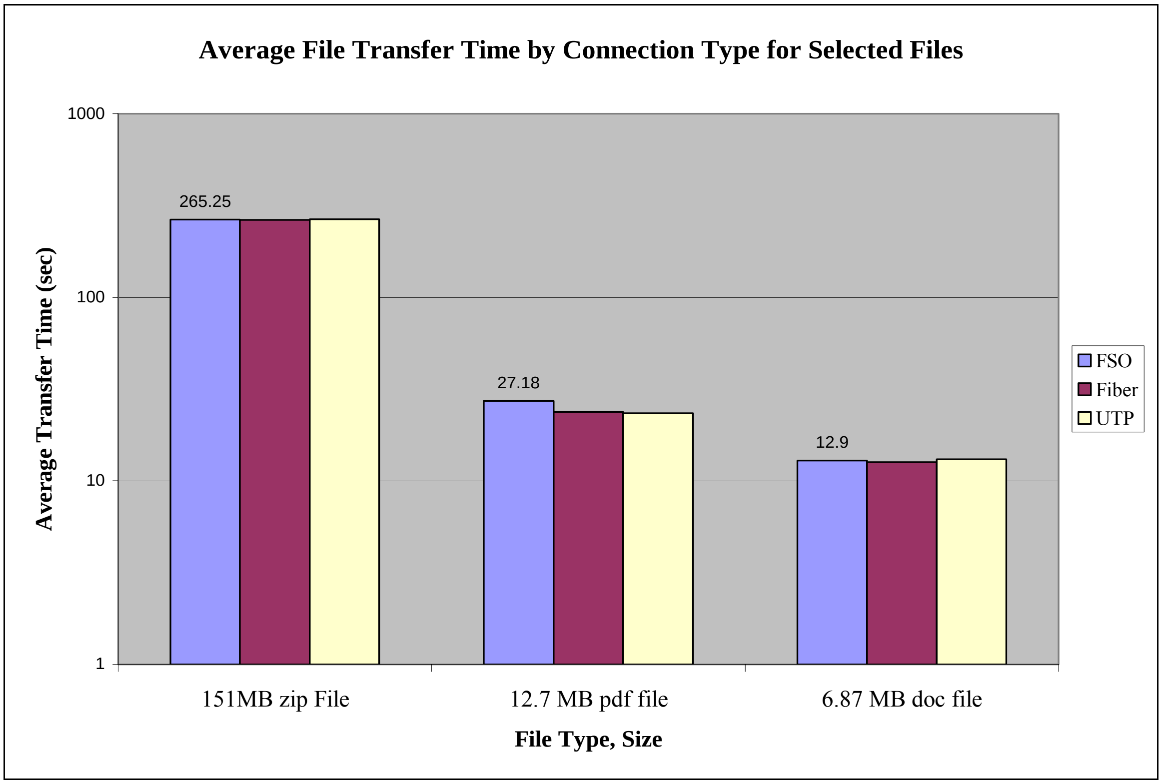

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Figure 23. Average file transfer time comparison. Time axis shown in logarithmic scale for clarity.

As a final check, we attempted to interrupt the FSO beam when a file transfer was in progress. A transitory interruption, by moving a hand or other object to mask the beam, did not reset the connection nor cause the transfer to abort. An interruption of roughly 12 seconds or greater was observed to cause the transfer to abort. There was no effect on a network connection due to a beam interruption. After an interruption of any length, the link merely reestablished itself. Streaming audio and video were downloaded through the FSO link with no discernible problems.

Table 2 shows the data obtained by measuring the voltage produced by a photodiode in response to the collimated beam from the transceiver as shown on Fig. 22. The procedure for obtaining this data was outlined in the previous chapter. A graphical view of the same data is shown on Fig. 24. We may use the following formula to derive the optical power from the measured voltage [30].

$$P = \frac{I_o e^{V/nkT}}{\Re(\lambda)} \tag{4.1}$$

where I_0 is the dark current of the detector, V is the measured Voltage, n is the ideality factor of the diode and $\Re(\lambda)$ is the responsivity of the photodiode. We use $kT = 0.026$ V at 300 K. $\Re(\lambda)$ at 1310 nm is 0.85 A/W [31]. In order to find the ideality factor of the photodiode and a precise value for I_0, a semiconductor parameter analyzer (HP4145B) was used. The resulting data is shown in graphical format in Fig. 25. Note that the y-axis is in logarithmic scale. The photodiode used was a Thorlabs FGA10 INGaAs high responsivity with an active diameter of 1 mm [31].

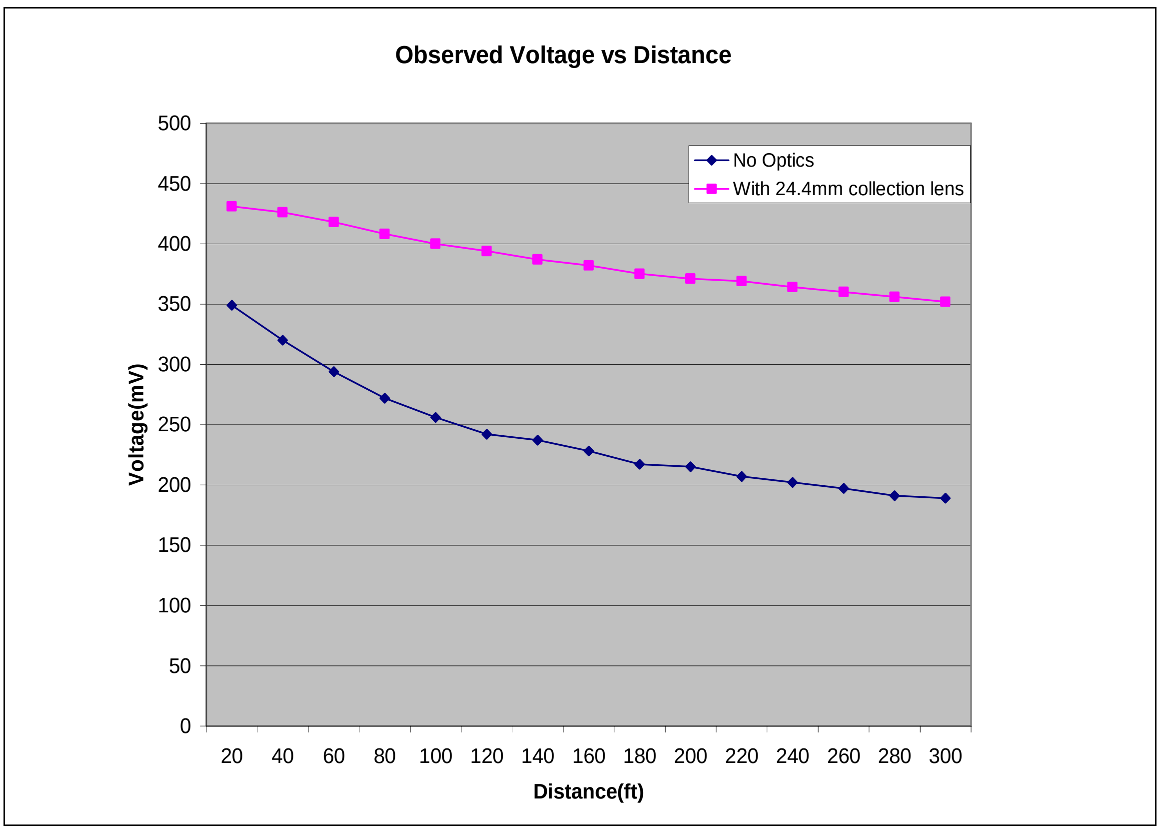

Figure 24. Graph of measured voltage vs. distance from transmitter using photodetector.

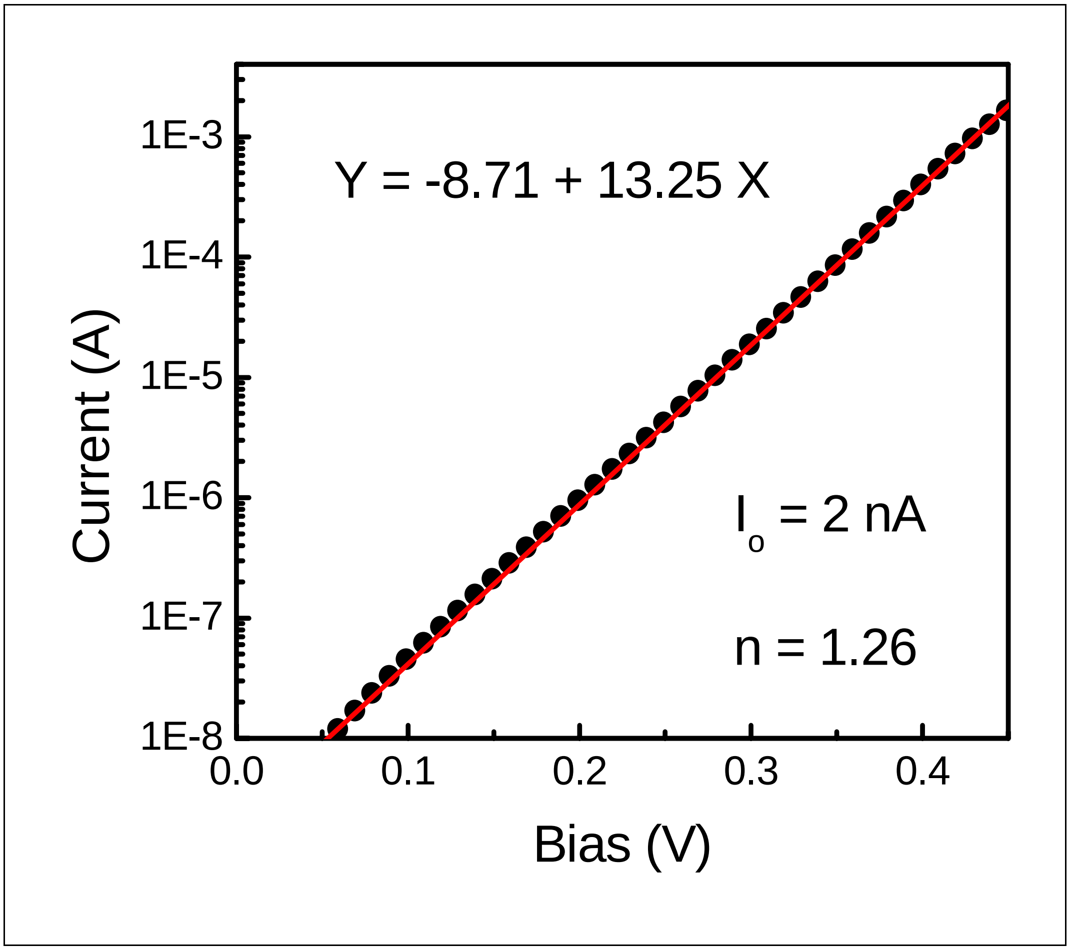

Figure 25. Graph of measured I-V characteristics for the InGaAs photodiode.

From this data we may calculate the power received by the photodiode as [30]:

$$P_P = \frac{I_P}{\Re(\lambda)} \tag{4.2}$$

where I_P is the photocurrent induced in the photodiode due to optical power P_P detected by the diode. Using the I-V curve shown in Fig. 25, I_P was found for each measured value of V. Figure 26 shows a graph of calculated power received vs. distance using this method.

This result is the most significant of the experiment. The calculated power at 10 ft using the measured voltage shows a value slightly higher than this at 1.308 mW,

slightly higher than the rated 1 mW output of the transceiver. (Rated power is measured as coupled into a single-mode fiber.) This is thought to be due to higher than the worst-case coupling efficiency into the multimode fiber being used for the experiment.

From data shown in Fig. 26 and Table 2, it is reasonable to conclude that, with the right collection optics, we can establish communications at this range and beyond (recall that the sensitivity of a typical detector is near -30 dBm.) From Eq. 2.4 we see that the received power is proportional to power of the transmitter. Therefore, if a more powerful diode could be used in the transceiver, the minimum detectable power could be received at a longer range. Why not simply use a transceiver with a higher powered LD? The problem lies in a safety issue. In order to minimize liability and keep costs low, manufacturers prefer to maintain the class I laser designations for transceivers. Therefore, they are not typically available with larger power ratings than 1 mW (max rating.)

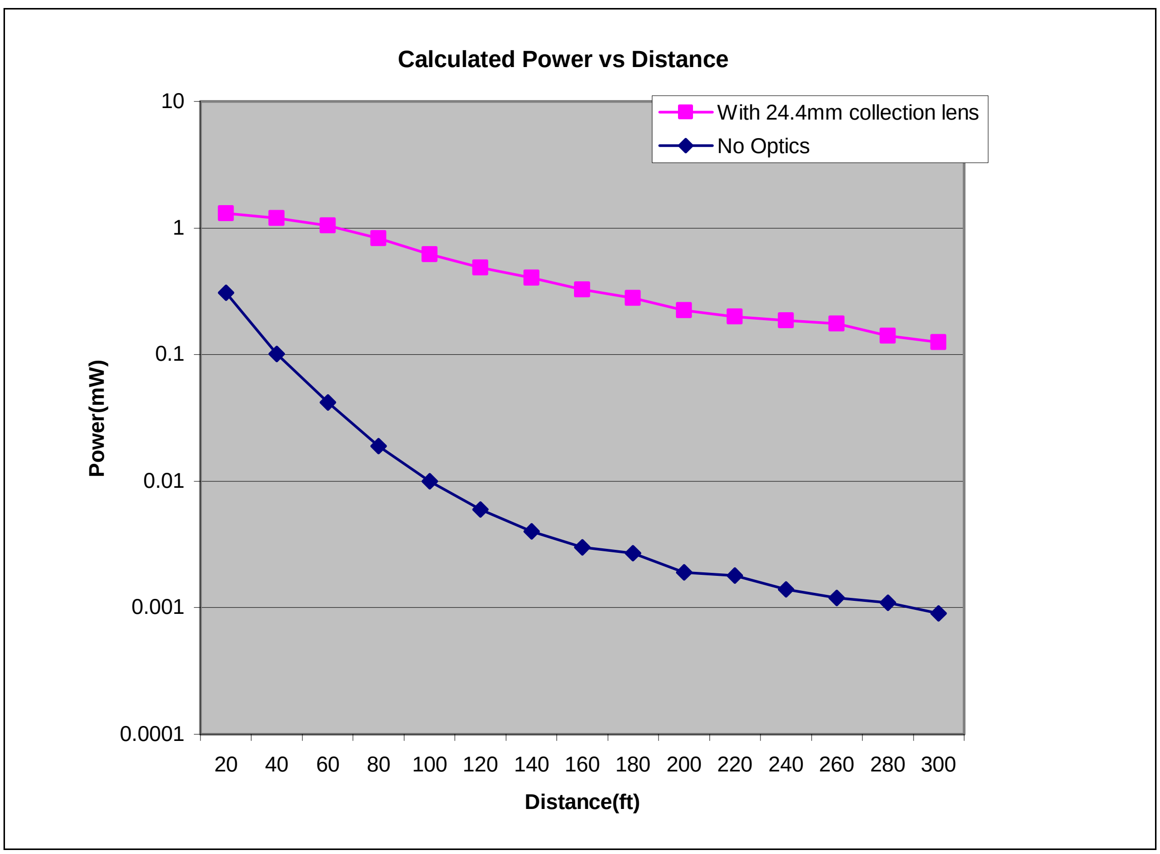

Figure 26. Logarithmic graph of calculated power vs. distance

Distance (ft)	Voltage measured with detector (no optics) (mV)	Calculated Power (no optics) (mW)	Voltage measured with 24.5 mm lens over detector (mV)	Calculated Power with optics (mW)
10	385	0.307	434	1.308
20	349	0.101	431	1.202
40	320	0.042	426	1.045
60	294	0.019	418	0.831
80	272	0. 01	408	0.618
100	256	.006	400	0.486
120	242	0.004	394	0.405
140	237	0.003	387	0.326
160	228	0.0027	382	0.28
180	217	0.0019	375	0.225
200	215	0.0018	371	0.199
220	207	0.0014	369	0.187
240	202	0.0012	367	0.176
260	197	0.0011	360	0.141
280	191	0.0009	356	0.125
300	189	0.0008	352	0.11

Table 2. Voltage measured with a photodiode at 20 ft intervals from the transmitter. The power values are calculated, based on the voltage.

In an effort to overcome the difficulties created by the minute receiver and limited power, an attempt was made to obtain a custom-designed 1x9 pin transceiver. Manufacturing houses were approached with requests for samples of a device with a higher power LD and also without fiber connectors. Shortly afterwards the author was offered some proposals for a custom-designed device that could have been a promising start. Time constrains prevented the purchase and testing of the samples offered. Figure 27 shows the offered designs. In the image on the left shows the LD and two choices for the receiver, a detector with a built-in lens and a flat window detector. The LD is rated at 7 mW and the detector at < -33 dBm sensitivity. The package could be plugged in to the socket we created. The center image shows a transceiver with a ball-lens detector. The right image shows the other option, a flat window detector. While these transceivers still require slight modifications to accept lenses, they give us more design options. As an example, the LD is equipped with a ball lens meant to collimate its output. We could observe the behavior of this beam and then use appropriate optics to modify it. Most importantly, we now get the access we need to the detector to place optics on it.

The successful transmission of fast Ethernet data confirmed that the circuitry is functional and that, in practice, a low-cost device could be employed as an FSO link. The power measurements further established that with optics, the modulated signal should be received with sufficient power, at least up to 300 ft as shown. It is clear, however that that the system needs to be optimized before it could be of practical use.

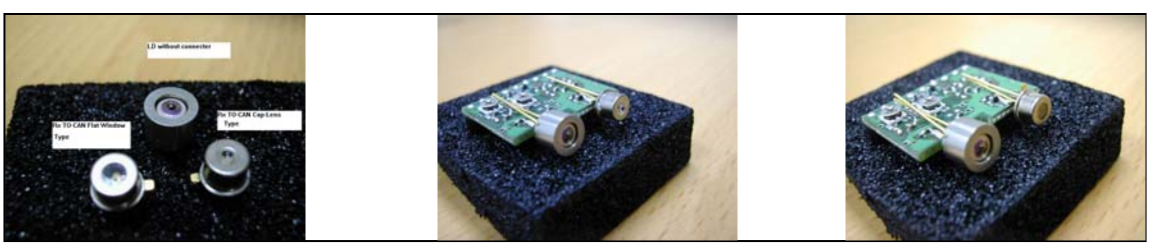

Figure 27. Custom-designed 1x9 transceivers offered by a manufacturing house in response to internet inquiry.

B. RECOMMENDATIONS FOR FURTHER RESEARCH

The author firmly believes that there is a military application for a small FSO device. It need not be an FSO Ethernet link. There may be a valid field application for a point-to-point voice link. Modulating a voice signal on FSO is fairly straightforward. This may be an area that could be explored by a future research project. The prototype is functional and would lend itself well to experiments in power, optics or data speeds. More research is needed in the effects of weather on the link as well. If a practical range could be achieved, there may be other applications that could benefit from a portable data linking device.

Further research is needed to find a simple scheme to align the transceivers. With an IR beam, this will always be a challenge. The author believes this could be done with a low power visible laser pointer attached to one of the devices. Another avenue to explore might be an aural indication of received power on a low-cost detector. A convenient and fast method to align the system is crucial to its utility.

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